

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A Virtual Design Studio for Low-Frequency Sound from  
Walking in Lightweight Buildings

NATA AMIRYARAHMADI

Department of Architecture and Civil Engineering  
Division of Applied Acoustics

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2019



A Virtual Design Studio for Low-Frequency Sound from Walking in Lightweight Buildings

NATA AMIRYARAHMADI

ISBN 978-91-7905-105-1

© NATA AMIRYARAHMADI, 2019.

Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 4572

ISSN 0346-718X

Department of Architecture and Civil Engineering

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Printed by

Chalmers Digitaltryck

Gothenburg, Sweden 2019



# **A Virtual Design Studio for Low-Frequency Sound from Walking in Lightweight Buildings**

NATA AMIRYARAHMADI

Department of Architecture and Civil Engineering

Division of Applied Acoustics

Chalmers University of Technology

## **Abstract**

In recent years there has been a growing interest for building lightweight multistorey wooden residential buildings in countries like Sweden with large and renewable forests. While positive aspects of these buildings, such as sustainability, ease of construction and lightness, motivate building more in wood, poor acoustic performance is a risk which concerns the wooden-building industry. Low-frequency impact sound from walking of the neighbors upstairs is the main source of complaints about the acoustic performance of these buildings. The disturbance caused by walking sounds, transmitted through lightweight wooden floors, results in acoustic discomfort and impairs the perceived quality of the building; sometimes even when the building has fulfilled an acoustic class higher than minimum requirement, according to the national standard on sound classification and its single number ratings. The standard methods for objective evaluation of impact sound insulation of floors cannot predict, at a satisfactory level, the walking sound annoyance that the inhabitants of wooden buildings experience. This causes an uncertainty about the resulting perceived quality of these buildings, which greatly concerns the building manufacturers and demotivates them from choosing lightweight wooden elements over heavyweight building materials such as concrete. This uncertainty can be overcome by evaluating the perceived acoustic quality of the building prior to its construction.

One solution is to build test houses where the subjective acoustic performance of floor samples can be evaluated in advance to the building construction. However, building a test house is expensive; besides, for evaluating the effect of every design modification on the experienced acoustic comfort of the building, a real floor sample has to be built and installed in the house, which would be time-consuming and costly. An alternative solution is to use virtual acoustic test facilities.

In this thesis a virtual design studio for impact sound is developed. It is a tool that facilitates creating and listening to the acoustic field generated by impact forces such as footsteps on lightweight floors. It also provides the possibility to evaluate the acoustic performance of floor elements in an early design phase, and to investigate the correlation between design parameters and the perceived impact sound insulation of the floor. The tool is demonstrated and a very first listening test shows that one can obtain results which are in good agreement with the results in literature. Loudness, reverberation and thumping are shown to influence the annoyance. It is also shown that there is a difference in judgement of walking sounds by persons who have experience with lightweight floors at home and by those who do not have that experience.

**Keywords:** Lightweight floors, Walking sound, Low frequency, Annoyance, Virtual design studio



## Acknowledgements

I would like to give my deepest gratitude first and for most to Professor Wolfgang Kropp, for being the most knowledgeable, motivating and supportive supervisor I could ask for. Also, for giving me the chance to be a member of Applied Acoustics group which has given me the best work experience of my life.

My sincere thanks also go to my assistant supervisor Krister Larsson for all the productive discussions we had and his insightful comments. I also appreciate being selected by him as an industrial PhD candidate and a co-worker at RISE Research Institutes of Sweden.

I thank my colleagues and PhD students at Applied Acoustics division for all the stimulating discussions and knowledge sharing, and above all, for the enjoyable moments we had together; especially our "handcraft" meetings. Julia, Alice, Laura, Penny, Astrid, Georgios, Carsten, Lars, Bart, Raul, you made this journey like passing through a flower garden for me.

Many thanks to Georgios Zachos for developing the code for my listening tests, and to Jens Forssén for proof-reading my thesis. Special thanks to Börje Wijk for being a great support for me when it came to experiments. Thanks for making things work so smoothly. I also appreciate our pleasant chats at Fika times.

I would like to thank my colleagues at RISE Research Institutes of Sweden for sharing their technical knowledge and giving me a helping hand with the experimental work whenever it was needed. I am especially grateful to Jonas Pettersson for his help with calibration of my measurement equipment which was almost always urgently needed. Also, my deepest thanks to Jan Almqvist, Håkan Andersson and Marianne Grauers for their support and for making it possible for me to finalize my PhD studies.

Maman, Baba, Shooka and Afsar joon, every second of everyday I feel grateful for having your continuous love and support in my life. Your encouragements and belief in me, gives me confidence to aim high and seek the best. Maman Bozorg you were always on my mind whenever I thought about the reasons I am here.

My dear Emad, you have been such a patient and supportive partner and friend. A lot happened in our life since I started my PhD studies, and we achieved the most beautiful things in life during these years. Thanks for supporting me all the way to another great achievement.

Dearest Dario, thanks for filling my heart with joy and making me laugh even at the most difficult moments of work. Also, thanks for teaching me how to work efficiently. I owe this to you my love.

The financial support received from Formas, the Swedish research council for sustainable development, for the project "A virtual design studio for low frequency sounds to create supportive indoor environments" (2016-01274) is hereby gratefully acknowledged. I would like to also to gratefully acknowledge the funding received from Formas and Vinnova, Sweden's innovation agency, within the project "AkuLite", which financed the first part of my PhD studies.





# Table of contents

Abstract .....	I
Acknowledgements .....	III
1 Introduction .....	1
1.1 Background .....	1
1.2 The need for a virtual design tool .....	2
1.3 Thesis objectives and research approach .....	4
1.4 Thesis outline .....	4
2 Input force characterization .....	7
2.1 Walking force measurements .....	8
2.1.1 Selection of an appropriate force identification method .....	9
2.1.2 Measurement setup for walking force identification using LMS method .....	11
2.2 Walking forces as the input to the auralization tool .....	15
2.3 Time-domain model of a standardized tapping machine .....	17
3 Simulating floor vibrations excited by walking forces .....	19
3.1 Analytical model of the floor .....	19
3.2 Application of the model to calculate floor vibrations due to walking .....	21
4 Impact force auralization .....	27
4.1 Design of the listening lab .....	27
4.2 Simulating floor vibrations with the sound reproduction system .....	28
4.3 Accounting for loudspeaker internal transfer function .....	29
4.4 Comparison with the field measurements .....	32
5 Listening test .....	35
5.1 Floor objects .....	35
5.2 Standardized impact sound insulation measurements using the virtual design tool .....	37
5.3 Design of the listening test .....	39
5.4 Results and discussion .....	40
5.3.1 Effect of familiarity with the walking sound .....	42
5.3.2 Naturalness .....	45
5.3.3 Correlations between the attributes .....	46
5.3.4 Discussion on floor designs .....	48

6	Conclusions and future work .....	51
6.1	Conclusion .....	51
6.2	Future work.....	54
	Appendix A.....	55
	Appendix B.....	57
	Bibliography .....	61

# 1 Introduction

## 1.1 Background

The increase of population and growth of urbanization has raised the tendency towards building multistorey dwellings to reside as many people as possible in the limited area of the cities. On the other hand, environmental concerns such as global warming and overuse of natural resources have attracted many countries towards applying green and renewable resources. One of the sustainable solutions to deal with the habitation of urban population is to build dwellings from wooden materials harvested from sustainably managed forests [1]. In countries like Sweden, with large forest area, there is great potential to increase the use of wood in multistorey buildings. In the past few years, the large investments by the Swedish government in the forest sector, together with reinforcement of EU policies against illegal harvest of wood, has insured sustainable application of wood in the country [2]. Between the years 2008 and 2010, the Swedish government appointed a delegation for sustainable cities to encourage urban development projects [3]. The outcomes were expected to reduce climate impacts, improve the environment and promote export of Swedish environmental technology. In this regard, using wood, which is a renewable and locally-available construction material, for building frames and components in dwellings was brought forward as a sustainable solution for continuous growth of urban areas. In addition, there are new technological developments, which make it possible to prefabricate wooden building modules in a well-controlled factory environment, simplify the building construction process and reduce the transportation and building costs to a great extent. These, all in all, have highlighted the usefulness of wooden building elements for a sustainable and continuous growth of urban areas today [4], and has resulted in a continuous growth in the application of wood in building multistorey dwellings [2].

In 1994, new Swedish building regulations were introduced that allowed building multistorey buildings with load bearing wooden elements, which had been forbidden for almost a century [5]. Today, about 10 % of the new multistorey residential buildings in Sweden are built in wood, but they have the potential to compete for 50 % of the building market by 2025 [6, 7]. During the past two decades, wooden building technology has improved in many aspects such as weather protection, fire safety, durability and energy efficiency. However, inadequate acoustic performance, especially poor impact sound insulation of buildings with lightweight wooden frames, makes using wood a risk for the building industry and a hinder for widespread application of wood as the main building material for multistorey dwellings [8].

In two residents surveys published in 2011 and 2013, the perceived acoustic performance of 15 lightweight multi-family buildings with different wooden elements was investigated, and compared with the acoustic performance of 6 concrete buildings [9, 10]. Different building techniques were applied in construction of the selected lightweight apartments, and the designs were representative for many existing buildings as well as new productions by Swedish building manufacturers. While the concrete buildings showed satisfactory acoustic performance, between 22 % up to 54 % of the people living in majority (14 out of 15) of the new wooden buildings reported being disturbed or very disturbed by impact sound, mainly generated by walking on the floor above. This high level of acoustic discomfort at one's home can have negative health effects and social consequences. While the impact sound can disturb sleep and deteriorate cognitive performance of the residents, the fact that it is generated by their neighbors, can affect the social aspects of living in the building.

Practice has shown that in some wooden buildings the noise disturbance is reported even when the building has fulfilled high standard classes according to Swedish regulations [8]. This lack of correlation between the objective standardized measures and perceived acoustic quality creates an uncertainty about the acoustic functioning of the wooden buildings that discourages the building industry from choosing lightweight wooden buildings over heavyweight building for example made of concrete.

Moreover, the widespread knowledge about poor acoustic quality of some wooden buildings, irrespective of the design, can cause a bad reputation for all multistorey buildings made of wood, which can eventually have a negative economic effect both for the builders and for the owners of such apartments.

In the past two decades, great efforts have been put into identifying both objective and subjective aspects of the noise problems in wooden buildings and into reducing the uncertainty about acoustic performance of these buildings. This has been made by improving the standard procedures for impact sound insulation rating by adapting them to the perceived annoyance of the low-frequency impact sound in lightweight wooden buildings. One of these projects that ran between years 2009 and 2013 in Sweden was AkuLite, which gathered a large group of national researchers, acoustic consultants and building manufacturers with the aim to develop sound and vibration criteria that are consistent with the perceived impact sound in lightweight buildings. The project outcomes indicated that by extending the frequency range of the impact sound measurements from 50 Hz down to 20 Hz, and using a spectrum adaptation curve with additional weight on the third octave frequency bands below 50 Hz, an 85 percent correlation between the objective measurements and perceived impact sound in lightweight buildings could be achieved [11]. However, this result was based on only 10 floor objects. In a more recent study by Öqvist et al. [12] that included 13 additional floors, it was shown that using AkuLite spectrum adaptation term for impact sound evaluation did not result in more than 65 percent correlation with the perceived annoyance. They suggested that by changing the lowest frequency band of the evaluations to 25 Hz instead of 20 Hz, the correlation could be increased to 77 percent (or 85 percent after excluding an outlier) for the tested floors. But this result is also provided for a limited number of floors (23 floors) and might change if more floor designs are included in the analysis.

In any case, the question remains whether characterization of the acoustic performance of wooden floors only with the help of energy-related quantities such as the impact sound insulation is sufficient, or a more perception-based characterization is needed.

## **1.2 The need for a virtual design tool**

The impact sound insulation of floor elements is often determined by a single-number quantity (SNQ) according to the international standard ISO 717-2 [13], using the impact sound transmission measurements in third octave bands or octave bands [14]. This SNQ rating is the basis for impact sound classification of spaces in buildings in Sweden [15]. To perform the impact sound transmission measurements between two vertically-connected rooms, a standardized tapping machine is often used as the excitation source. The continuous impacts of the steel hammers of the tapping machine excite the floor modes in the upper room over a wide frequency range, and the generated sound by the impacts is measured in the room below. A correction term is then applied to the measured impact sound levels to compensate for the dissipation of acoustic energy due to the room absorption. Finally, a

spectrum weighting procedure is used to obtain the SNQ for impact sound transmission of the floor element.

Although the impact sound SNQ rating method is to some extent representative of the total acoustic performance of floors, it does not give any information about how a floor isolates some frequencies, or how it performs when excited by different excitation sources. The frequency-dependent impact sound insulation of the floor becomes more important when the structure is excited by low-frequency impact sources such as human footsteps that have their most energy below 50 Hz. Moreover, at these frequencies due to the low number of modes, the diffuse field condition of the measurements no longer holds, and the impact sound measurement results become dependent on the receiving room properties, the positions of the tapping machine on the floor and the microphone positions in the receiving room.

Furthermore, the fact that the impact sound transmission data of the floor are often acquired in third octave bands increases the uncertainty of the floor performance evaluations at low frequencies. The reason is that the tapping machine, used as a broadband impact source to excite the floor modes in the standard measurements, has a base frequency of 10 Hz. At low frequencies, due to the narrowness of the third octave bands, the hammer impact spectrum has only one sharp peak at a single frequency, while at the remaining frequencies in that third octave band, the floor receives very little energy. At these frequencies, the performance of the floor remains undefined. It means that a strong floor resonance, at a frequency different from that of the tapping machine spectral peak, combined with an impact excitation with high energy content at low frequencies, can result in low-frequency sound disturbances which are not predicted in the objective evaluations. Therefore, even when the impact sound insulation evaluation of a lightweight floor is made down to 20 Hz using the new adaptation terms, no more than 85 percent correlation between the objective evaluations and occupants' rating of annoyance is achieved [11].

One way to improve the low correlation between objective impact sound measurements and the subjective acoustic quality of the floor, in order to reduce the uncertainty about the acoustic performance of future lightweight buildings, is to perform occupants' surveys in all types of existing lightweight buildings with different designs and all possible combinations of building elements. However, such a solution is very time-consuming, costly and unfeasible due to lack of access to all such buildings, and the uncertainty about willingness of the occupants to participate in the survey. Moreover, these surveys only report about the perceived acoustic performance of existing buildings, but they cannot provide any information about new building solutions. Another way to tackle the uncertainty about acoustic functioning of new buildings is to build test houses where the subjective acoustic performance of new floor solutions can be evaluated before being used in a real building. But this solution is also expensive and time consuming since for testing every design modification, a floor sample has to be built and installed in the house.

An alternative solution is to use virtual testing. In this case, many variations of floor design as well as impact sound sources can be simulated, and the listening tests can be made by as many participants as required. In this thesis, a virtual design studio for low frequency impact sound is developed. This virtual design tool can be used by building manufacturers to gain an insight about how the impact sound insulation quality of the building will be perceived, before it is built and/or before the tenants have moved in. This tool can also be used to thoroughly investigate the coupling between floor design parameters and the perceived impact sound. These types of studies are very difficult to carry out in real

experiments or even in the field, as it is hardly possible to have control over all parameters of importance. In addition, such an approach would be very expensive.

To carry out such studies in a virtual environment hopefully opens a completely different way of tackling the problem to find designs for wooden floors providing good acoustic performance.

### 1.3 Thesis objectives and research approach

This thesis presents a virtual design studio for low-frequency impact sound. It includes simulation of the excitation, the floor vibrations and the radiation of the impact sound from the floor into the receiving room. The thesis focuses on auralizing the impact sound induced by walking on lightweight floors, which is the most common and the most disturbing impact sound source [16], especially in lightweight buildings [9].

To develop the virtual design tool for impact sound auralization, different objectives had to be achieved in this thesis. The objectives are as follows.

- To develop a method which allows for measuring the forces when a person walks on a floor. The method should be applicable for any person with arbitrary shoes or even barefoot.
- To establish an adequate model for lightweight floors allowing to calculate the vibrational response of the surface due to a given excitation. This approach should be as flexible as possible allowing for even more complex models than used in this thesis.
- To develop an auralization tool to be able to listen to the sound field created by the vibration of the floor in an environment that is as natural as possible.

In addition, the overall objective of the thesis is to combine these three elements to one tool and demonstrate the function of this virtual design tool by a final listening test.

### 1.4 Thesis outline

The thesis elaborates on the required steps for developing a virtual design studio for impact sound as follows.

**Chapter 2** presents the approach to obtain the forces due to walking. The measurement technique, based on a least-mean-square (LMS) algorithm as developed and applied within the PhD project, is demonstrated. The chapter provides a brief background on this technique and describes the experimental approach in this thesis as well as the technical challenges to identify low-frequency transient forces such as human footsteps. The formulation and development procedure of the LMS-based force identification technique as well as its application in identifying the differences between footstep-induced forces and the impact forces generated by a standard tapping machine on lightweight floors are dealt with in the appended *Paper I* and *Paper II*.

**Chapter 3** elaborates on how floor vibrations induced by footsteps, as the source of walking sound radiation, are simulated. Three analytical floor models are presented, for isotropic, orthotropic and prestressed orthotropic floor. Moreover, the numerical approach for calculating the floor vibrations of the entire floor, induced by a sequence of walking forces, is described here.

**Chapter 4** presents the procedure for auralizing the walking sounds using floor vibration signals. It describes how low-frequency vibrations of a floor excited by walking can be represented by a discrete

mesh of mid-to-high frequency-range loudspeakers and subwoofers, and how the floor vibrations can be translated to input voltage of the loudspeakers. The properties of the listening laboratory and the sound reproduction system built for auralization of impact sound are presented as well. To demonstrate the ability of the presented virtual design tool in reproducing the impact sound, the walking sound measured in situ and the auralized version of the sound in the laboratory using the simultaneously measured floor vibrations are compared.

**Chapter 5** finally demonstrates the complete setting of the virtual low-frequency design studio. It shows the results from virtual impact sound insulation measurements where a number of different virtual floors are excited by a virtual tapping machine. The chapter also presents the results of a listening test designed for subjective assessment of the virtual design tool for walking sound. The ability of the virtual design tool in reproducing plausible walking sounds and reflecting the perceivable variations in the floor design are discussed.

**Chapter 6** concludes the findings of the PhD thesis, and briefly discusses possible future developments of the work.





## 2 Input force characterization

Selecting the impact source and providing the data representing the input excitation to the floor structure is the first step in developing the virtual design tool for impact sound presented here. When characterizing an impact source, it is important to determine how it interacts with the floor structure and what type of excitation it generates.

In the book *Structure-Borne Sound*, by Cremer et al. [17], the structure-borne excitation sources, depending on their interaction with the structure, are divided into three categories: ideal velocity sources, ideal force sources and non-idealized sources. It is the ratio between the mobility of the source and the receiver which determines what category the source belongs to, and whether an excitation is force or velocity driven, or a combined excitation.

If a structure is connected to an ideal velocity source, at the contact point between them, the structure vibrates with the same velocity as the source. For an ideal velocity source, the condition below holds

$$|Y_S| \ll |Y_{R_i}|; \forall i, \quad (2.1)$$

where  $Y_S$  is the mobility of the source and  $Y_{R_i}$  is the mobility of the receiving structure at any contact point  $i$ .

For an ideal force source, independent of the receiving structure, the excitation force at the contact point between the source and the receiver remains the same. For such a source the relation below holds

$$|Y_S| \gg |Y_{R_i}|; \forall i. \quad (2.2)$$

For a non-idealized source, the velocity of the receiving structure at the contact point is a function of the velocity of the free source before connecting it to the receiver as well as of the mobilities of the source and the receiver,

$$v_R = \frac{v_{FS}}{(Y_S + Y_R)} Y_R, \quad (2.3)$$

where  $v_{FS}$  is the free source velocity. The contact force between the source and the receiver is also dependent on the interaction between them. Therefore, the force cannot be modelled independently of the receiver structure.

It can be said with great certainty that none of the common impact sources in buildings fit the ideal velocity source category. Even lightweight floors in wooden buildings are designed and dimensioned carefully to bear heavy static loads from the weight of the floor and all the furniture on it, as well as the dynamic loads from common impact sources. These floors are designed with enough mass, stiffness and damping not to vibrate with large velocity amplitudes under a common excitation like walking. Thus, vibrations of a lightweight floor under footsteps might not be velocity driven.

On the other hand, most impact excitations in buildings fit in the ideal force source or non-idealized source category. In *Paper I*, we have measured walking forces generated by six persons walking on two lightweight joist floors with different mass and stiffness properties. As described in the paper, changing the floor properties did not result in dramatic systematic changes in the temporal and spectral contents of the walking forces. This would imply that walking forces on a lightweight floor structure do not have a significant dependence on the properties of the floor. Thus, for our application, as a

reasonable approximation, the same set of measured walking force signals could be used as input to any floor model without taking the foot-floor interaction into account.

However, later in the project, when auralizing floor vibrations by means of such measured walking forces, it turned out that there is an – even so small – influence of the floor on the measured forces and that this influence is audible. Despite this, the walking force data obtained from measurements on the lightweight floor structure in *Paper I* are used for auralization here (in a modified form), as no model was available that could provide walking force data including foot-floor interaction under realistic walking conditions on a real lightweight floor. Also, due to the individuality of the footsteps, developing a realistic model for walking forces requires collecting a large amount of data for a vast number of people under different walking conditions, and studying the influence of different parameters on the walking forces. Performing such a statistical study was outside the scope of this PhD project. Therefore, for auralization of walking sounds, only the walking forces acquired by measurements here were used, and measures were taken to exclude the influence of the lightweight floor on the measured data, as further described below.

## 2.1 Walking force measurements

Measuring forces acting on a structure is of high importance for different design and maintenance purposes in engineering applications. Impact forces measured under realistic walking conditions on different lightweight floors can be used in different applications, such as the virtual design tool in this thesis, for function-oriented design improvement of lightweight floors as well as for better adaptation of the impact sound evaluation procedures to the behavior of lightweight floors under footstep excitation.

In literature, several measurement techniques are suggested to determine the ground reaction forces generated by the foot during walking, also known as stance forces or walking forces [18, 19, 20, 21, 22, 23]. The majority of these measurement techniques are based on direct measurement of forces induced by footsteps and require the test subject to walk on a surface other than a real floor. The surface can be for example an instrumented treadmill equipped with force plates [20, 21] or a fixed force plate [18, 19] that the walker needs to take only one step on. In some cases, in order to give more freedom to the walker to choose the walking path, the walker has to wear special shoes that have force transducers attached underneath [22, 23]. However, all these methods might manipulate the natural walking by imposing limitations on for example the number and direction of steps, the walking pace, the walking surface and the type of footwear. Thus, it is very likely that the data obtained from these measurements cannot be applied as a general solution for investigating walking forces generated by walking on real floors with or without footwear. To obtain more accurate and realistic walking force data, the measurements should be made directly on real floors, under natural walking conditions, and not on special force measuring devices with all the mentioned limitations. However, direct measurement of the stance forces without using a force sensor at the contact point between the foot and the floor, without affecting the stance force, is almost impossible. Therefore, an indirect measurement method is needed to measure stance forces on the floor independent of the walking style, walking surface and type of footwear. An indirect measurement method to acquire vertical force signals induced by walking under realistic conditions was developed during this PhD project, *Paper II*, which is briefly presented in the next sections. The tangential components of the forces are not studied here because of

their significantly lower amplitudes compared with the vertical forces [24], and thus their less influential effect on the walking sound.

### **2.1.1 Selection of an appropriate force identification method**

The methods that are used to determine input forces of a system, using known transfer functions and system responses, are generally called inverse force identification methods. Force identification methods are commonly used when mounting force transducers directly at the excitation points is impossible. This can be due to the spatial limitations to reach the excitation point or due to the fact that using a force transducer between the exciter and the structure alters the loading mechanism. The latter is the case when measuring contact forces between the foot and the floor during walking.

In force identification problems, determining the location of input forces prior to force prediction is of high importance, because it can transform an ill-posed inverse problem to a well-posed problem. Depending on the available information about a dynamic system, the force identification problems can be divided into two categories; localization of input forces and reconstruction of them. When the position and number of excitation forces of a system are unknown, a force localization algorithm using a full model of the structure together with the system responses is needed to identify the forces. In literature, a number of methods are presented on how to localize input forces of a system when the excitation points are not easily detectable, see e.g. [25, 26]. On the other hand, for a system with known excitation points, availability of a full system model is not necessary. For such a system it is possible to form the force identification algorithm and reconstruct the input forces using only the transfer functions between the excitation points and the selected response positions. In walking force measurements, it is possible to determine the location and the number of footsteps by tracking the walker. Therefore, force location prediction is not required, and the force identification method can be used only to reconstruct the forces.

Many force identification methods are available in the literature, for example in [25, 27, 28, 29, 30]. These methods can all be divided into two categories; direct methods and optimization or indirect methods. The direct methods identify forces by directly multiplying inverted transfer functions of the system with the measured responses. The indirect force identification methods are based on matching the estimated and measured responses. All of these methods have their own advantages, limitations and drawbacks. For example, a direct method such as modal decomposition [29] or inverse structural filter (ISF) [28], can provide a more straightforward solution compared with an indirect method, but very often ill-posedness, singular-value errors and high sensitivity to errors in the measured or modelled data are resulting from inversion of frequency or impulse response functions, which can affect the accuracy of such methods. Overcoming these errors requires additional effort such as creating over-determined systems or applying strategies to reject small singular values, which makes the solution complicated. On the other hand, in the indirect methods such as sum of weighted acceleration technique (SWAT) [27] or the transmissibility-based method [25], the measurement error and the optimization approaches which are used to minimize the estimation error can cause inaccuracy in the predicted input forces. It seems, there is no single always-well-working solution for force identification problems, and depending on the intended application and characteristics of the system, one has to choose a particular method to obtain the input forces of a system with the highest quality.

A challenge when dealing with force identification problems is the description of the system. Many force identification methods, such as SWAT, modal decomposition and virtual field [30], require a full

structure model to obtain transfer function data. These models can be acquired using different approaches such as analytical and numerical (FEM) models, or modal analysis experiments. In this case, extra effort is required to obtain a full structure model for a single structure, and the accuracy of the measured input forces depends on the accuracy of this model. When using a force measurement technique for a broad application, such as measurement of walking forces on different floor structures, using methods that require full structural models would be very time-consuming and impractical. This is because one would need to model the full structure every time that a new floor is to be tested. In such cases it is better to use an alternative force identification method that allows for describing the system behavior with as little data as possible.

The majority of force identification methods are formulated in the frequency domain and only a few approaches are used to solve the inverse problem in the time domain. Frequency-domain methods are commonly used for investigating forces generated by steady-state processes, such as the forces induced by engines into vehicle frames or by propellers into ship hulls. Time-domain methods are suggested for transient forces when the variations of a force over time play an important role in the response of the structure. Due to the variations of both signal and excitation position of walking-induced forces over time, a time domain solution is certainly favorable here.

Therefore, the indirect force identification technique based on the LMS (Least Mean Square) algorithm [31] is applied in the following. In the LMS-based force identification method, the input forces of a linear system are estimated using the system outputs at selected receiver positions and the impulse responses between the excitation points and the receiver points. The forces estimated in this way are then used to reconstruct the system responses. By comparing the measured and reconstructed responses, the estimation error can be calculated. The estimation error is then used to optimize the estimated forces through an iterative process where the optimization criterion is based on the convergence of the mean quadratic error towards its minimum value. The schematic drawing presented in Figure 2.1 shows in principle how the estimation error is used to calculate the impact force in an iterative process.

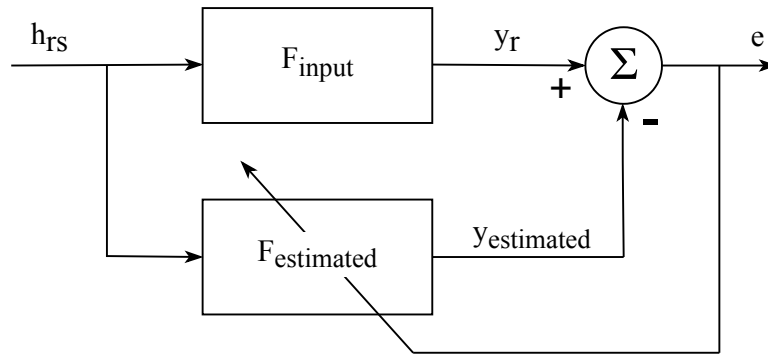


Figure 2.1 Schematic drawing of a recursive force identification algorithm

For a linear multiple-input-multiple-output (MIMO) system, the relation between the input forces,  $F$ , and the outputs of the system,  $y$ , at every receiver position  $r$  and the time step  $n$  can be formulated as

$$y_r(n) = \sum_{s=1}^S \sum_{i=0}^{I-1} F(n-i)h_{rs}(i), \quad (2.4)$$

where  $h_{rs}$  represents the impulse response function between the source  $s$  and the receiver  $r$ ,  $S$  is the total number of excitation forces and  $L$  is the length of the impulse response functions.

In our measurements, to solve for the forces, as the first step, all the force signals were assigned with initial values. For simplification, the initial values were chosen to be zero. Having the initial force values and the known impulse responses, the system response at the receiver positions,  $\xi_r$ , could be reconstructed. The estimation error was then calculated using the following equation,

$$e_r(n) = y_r(n) - \xi_r(n). \quad (2.5)$$

The mean value of the quadratic error was calculated as

$$E[e^2] = E[(y_r(n) - \xi_r(n))^2]. \quad (2.6)$$

By taking the derivative of the mean quadratic error,  $E[e^2]$ , with respect to the input forces,  $F$ , the gradient towards the minimum quadratic error is obtained. The quadratic error gradient is then used to update the force value in the respective iteration, and this process continues until the minimum estimation error is achieved.

In practical applications, such as our walking force estimation, sometimes the estimation error converges to a constant, with a non-zero but very small value, and from there the changes of the updated forces, compared with the calculation cost, are minor. In these situations, instead of aiming for a zero quadratic error gradient, the number of iterations and a small non-zero error value can be chosen as the convergence criterion of the LMS algorithm.

In the equation system which is formed in LMS algorithm, the number of receiver points should be at least equal to the number of excitation points. However, using the minimum number of receivers increases the sensitivity of the method to measurement noise. For example, if in one of the receiver signals there is a strong background noise, the algorithm will take the noise as one of the responses of the structure and adapts the estimated forces also in accordance with the noise. To reduce the susceptibility of the solution to measurement error, and make the algorithm more robust, an over-determined system with more receiver positions than number of input forces is recommended.

The LMS-based force identification method has shown to be a reliable tool in different applications [32, 33, 34]. For this method, no analytical or numerical models are required to describe the behavior of the system. The transfer functions of the test structure can simply be obtained by using measured impulse response functions between the known excitation points and a number of selected receiver points. A full description of the LMS-based force identification method used for measuring walking forces on lightweight wooden floors is presented in the two articles *Paper I* and *Paper II*.

### 2.1.2 Measurement setup for walking force identification using LMS method

In an initial test phase, accelerometers (B&K type 4374) were applied to measure the responses of the floor when excited by a shaker (LDS type V406). The frequency response functions (FRFs) between the shaker and the accelerometers were measured and then converted to impulse responses (IRs) using the inverse Fourier transform. This setup is appropriate for measurement of both steady-state and transient forces at frequencies above 10 Hz. Below this frequency, the estimated forces were dominated by noise (see e.g. Figure 2.2) due to the low frequency limit of the shaker at 10 Hz.

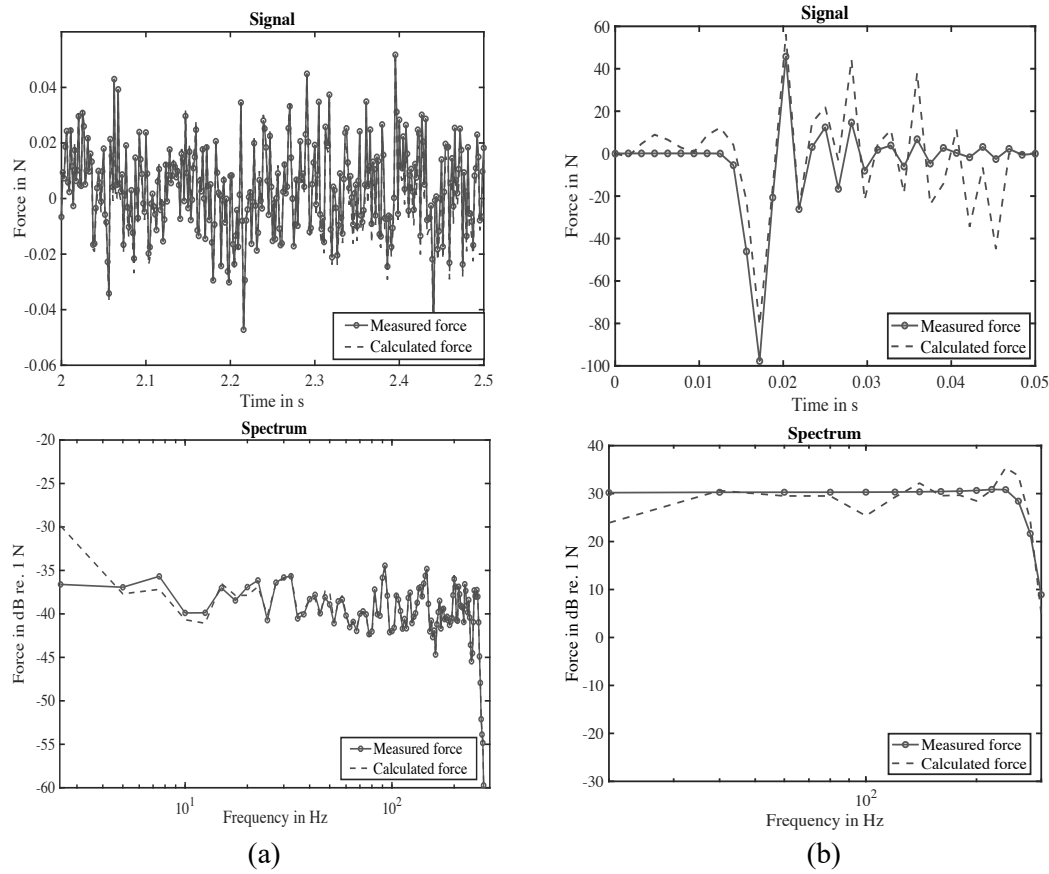


Figure 2.2 Comparison between direct measurements and LMS-based calculation of (a) a steady-state random force generated by a shaker, (b) a single impact force generated by an impulse hammer. Response signals at four and three receiver positions respectively are used to estimate each input force.

The walking forces have their maximum energy at very low frequencies, mainly below 100 Hz. A significant part of the energy that is transferred from the foot to the floor during walking is due to the mass-loading resulting from the weight of the walker. To be able to measure this force, the lower limit of the measurement frequency range should be as low as 0 Hz. In order to measure the impulse response functions including the very low frequencies, a handmade impulse hammer is used instead as the excitation source. To minimize the possible errors caused by the uncertainties in the location and direction of the hammer impacts in IR measurements, the impulse responses were measured 20 times and the average IR at each position was used in the LMS force identification algorithm.

Although the hand-made impulse hammer provides reliable excitation forces down to zero frequency, the static part of the force, induced by a footstep, cannot be analyzed when using accelerometers, as they do not measure the DC part of the signals. Figure 2.3 shows an example of the walking force measurement results when accelerometers are used to obtain floor vibration signals.

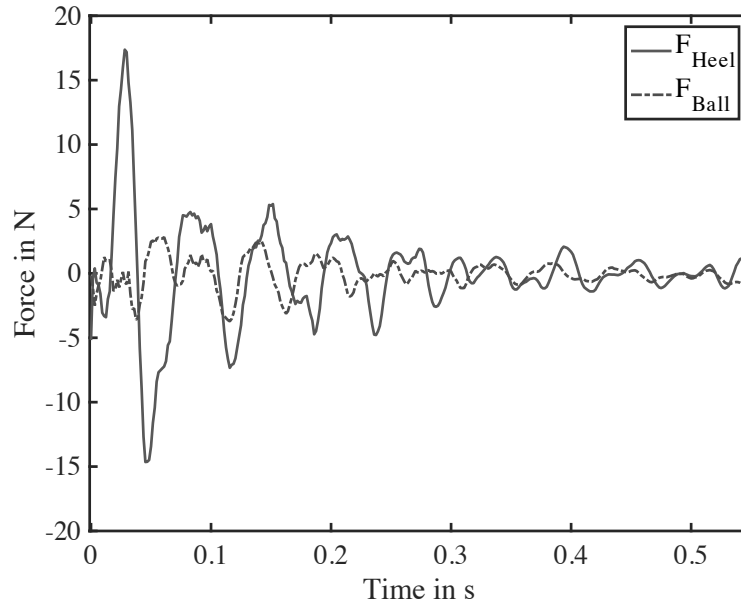


Figure 2.3 Contribution of the heel and the ball of a foot in a single footstep force calculated by using accelerometer signals in the LMS algorithm.

The basic characteristics of standard piezoelectric accelerometers do not allow for measuring near 0 Hz accelerations [35]. Because of the finite resistance and capacitance of these sensors, charge leakage due to near zero frequency loading is inevitable [36]. Therefore, they cannot be used to measure static deformations of a structure.

Therefore, we replaced the accelerometers with strain gauges. A strain gauge sensor consists of a conductive metal wire or foil which is bound to an electrical insulation base and is attached to the gauge lead, see Figure 2.4. The ready-made strain gauge sensors are often made as a very thin film (in micrometer order), and are self-adhesive, which makes it easier to attach them tightly on the test structure. The operation principle of strain gauges is based on the change of electrical resistance in the conductive metal when exposed to compressions and elongations.

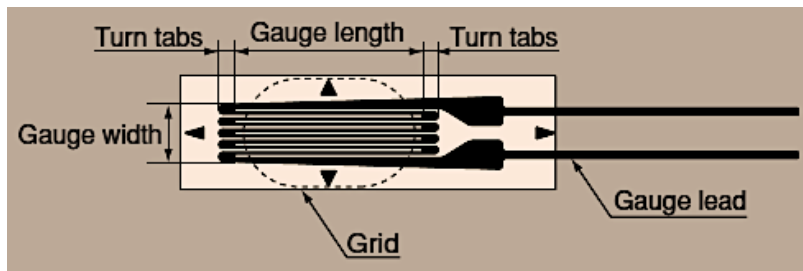


Figure 2.4 Structure of a strain gauge (reproduced from TML Strain Gauges catalog [37] after permission from Tokyo Measuring Instruments Lab.).

When a floor structure is exposed to external forces such as walking, it deforms. The deformation causes compressive and tensile strains in the structure. These structural strains transmit via the gauge base (electrical insulation) to the conductive wire or coil of the strain gauge attached to the surface and stretch and compress it. This causes changes in the electrical resistance of the sensor, which are proportional to the structural strain. The relation between variations in resistance and strain is presented below:

$$\varepsilon = \frac{\Delta L}{L} = \frac{\Delta R/R}{K}, \quad (2.7)$$

where  $\varepsilon$  is the measured strain,  $R$  is the gauge resistance,  $\Delta R$  is the resistance change due to the strain and  $K$  is the gauge factor given on the data sheet of the strain gauges.

The strain-based measurement mechanism of these sensors gives them the ability to measure both static and dynamic deformations of a structure, as long as the deformations remain in the elastic range of the sensors. Therefore, these sensors were applied to measure structural responses of the floor in our walking force measurements.

Figure 2.5 illustrates an example of a single footstep force measured using the LMS force identification technique. The force is obtained by superposition of two forces generated by the contact between the heel and the ball of the foot with the floor during walking. These forces are separately reconstructed by the LMS algorithm.

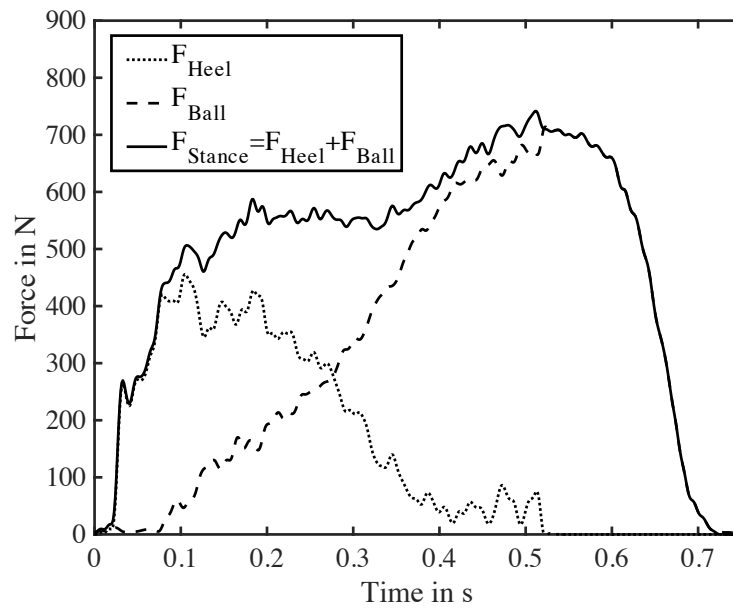


Figure 2.5 One footstep force generated by a 59 kg barefoot walker on a wooden floor. Solid line: total footstep force; dotted line: heel contribution; dashed line: ball contribution.

Depending on the number of footsteps that were measured, we always used two more strain gauge sensors than the number of excitation forces (e.g. at least 8 sensors to measure 3 steps), in order to make a sufficiently over-determined equation system. The over-determination can reduce the sensitivity of the algorithm to the measurement noise, however, the position of the receiver points have to be chosen carefully. At some positions on the structure, where the vibration amplitudes were small, the background noise of the sensors were in the same order as the floor responses. This resulted in erroneous estimated forces. Therefore, before the walking force measurements, by using hammer impact measurements, positions with high signal to noise ratio were identified, and the strain gauges were then attached at those positions.



## 2.2 Walking forces as the input to the auralization tool

Several sets of walking force measurements were made using 6 different walkers (3 males and 3 females), both with and without shoes. A maximum of three steps per walker were measured.

In the walking measurements, the practical issues such as the limitations in the number of sensors and measurement system channels, the effort required for identifying proper sensor positions and measuring transfer functions and the calculation time for every measured walking force, puts a limit on the number of consecutive steps that can be measured. While in the auralization tool, there are no such limits for the number of simulated footsteps on the floor. The calculation time is within reasonable limits, e.g. the calculation of floor responses for 20 consecutive steps and generating the audio signals for auralization takes less than 15 minutes. Therefore, we have the freedom to create different walking sound scenarios by making an arbitrary force signal containing a chosen walking path, with as many steps as needed and a combination of different walking forces. The force signals that were used in our experiments had an upper frequency limit of 120 Hz due to the limited signal-to-noise ratio imposed by the strain gauges and were taken both directly from walking measurements and from modifications of the measured forces. The modifications were applied on different phases of stance force to create variations in the speed and magnitude of the force in that stance phase. For modification, the original walking forces were divided into 4 different pieces consisting of the initial contact, loading response, midstance and terminal stance phases (see Figure 2.6), where each piece could be modified separately. To preserve the continuity of the footstep force signal, the beginnings and the ends of the consecutive pieces were used as the reference points for ending and starting the modified pieces respectively.

Since our earlier studies, presented in *Paper I*, implied that changing the lightweight floor properties does not have a noticeable effect on the walking forces, we assume that the measured forces on the floor in our experimental setup could directly be used as the input excitations for the model floors.

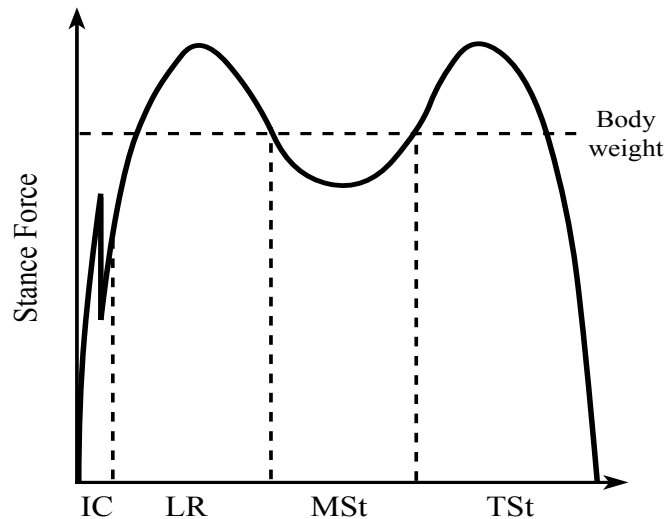


Figure 2.6 The measured single footstep force signals were divided into four pieces, where each piece could be modified independently. The pieces consist of: initial contact (IC), loading response (LR), midstance (MSt) and terminal stance (TSt).

An example of a modified single footstep force is shown in Figure 2.7.

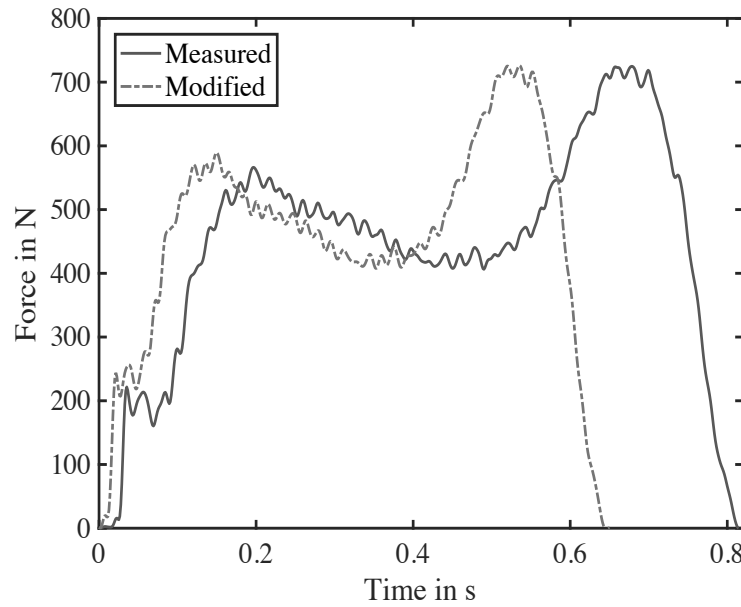


Figure 2.7 The original measured single footstep force of a barefoot walker vs. the modified version with an increased speed by 20% and amplified heel impact magnitude by 30%.

By using a mixture of measured and modified single footstep forces, several walking scenarios on the floor were generated for the very first listening experiments. When carrying out the initial listening tests with simulated signals, an unrealistic sound almost like a ringing appeared with each step. It turned out that the cause was in the measured forces. In *Paper I* and *Paper II*, it was stated that the walker could be generally considered as a force source, i.e. the influence of the floor on the measured force is negligible, meaning that the walker is an ideal force source. Although this is true over a wide frequency range, in the vicinity of the very first floor resonances this does not seem to be true. This was also observed by Lievens and Brunskog in [18] and is actually visible in e.g. Figure 13b in *Paper I*. There the measured forces for a wooden floor and a cement-wood floor are compared. Although both spectra are very similar at the first resonance frequency of the wooden floor (i.e. around 24 Hz) there are clear differences at some frequency components. These frequency components are also observed in the time records of the forces as small fluctuations around the general shape of the curve and were clearly audible in the auralization. The first idea could be to low-pass filter the force signal. However, there is a severe drawback in that as the very first slope of the measured force would be reduced as well. This slope, created by the impact of the heel, determines strongly the strength and the character of a step. Therefore, it is essential to preserve the very first slope which would not be possible when just low-pass filtering the signal. Instead, a smoothing technique is applied where the force signal is first resampled at a higher rate, by a factor 10. The resulting time signal is represented by a limited number of discrete values (see Figure 2.8) and spline interpolation is used to recreate a smoothed shape of the force record. To avoid discontinuities at the boundaries of each segment defined by the discrete points, a moving average over 5 samples is applied before resampling the time record to the original sampling frequency.

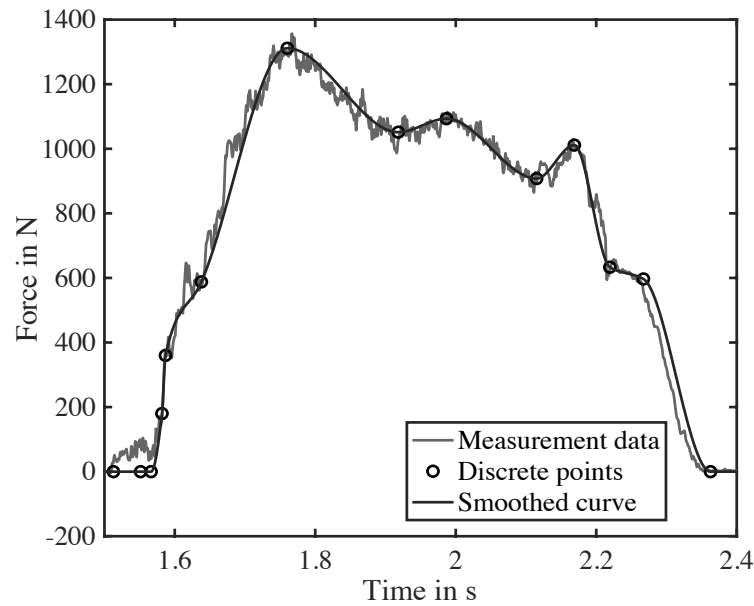


Figure 2.8 Segment-wise curve smoothing of the footstep force signal.

The corresponding spectrum of the time signal, reconstructed with this technique, is shown in Figure 2.9. When the resulting forces were used in walking sound auralization, the resulting sounds were free from the artifacts we observed before and sounded much more plausible and comparable with the measurements.

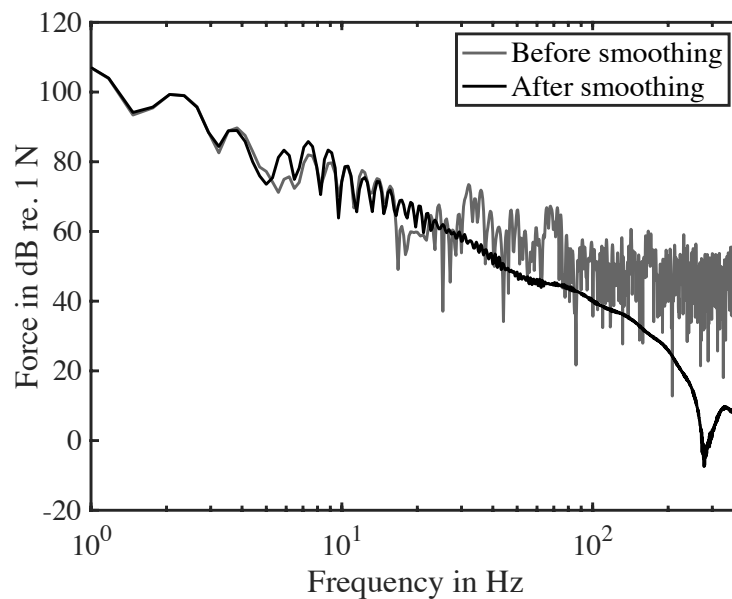


Figure 2.9 Single footstep force spectrum before and after applying the curve smoothing technique.

## 2.3 Time-domain model of a standardized tapping machine

The virtual design tool for impact sound can be used to auralize the sound generated by any impact source, provided that model or measurement data of the impact forces are available. An important reference impact source in building acoustics is the standard tapping machine. Auralizing the impact

sound generated by a tapping machine on a virtual floor allows for predicting the impact sound insulation of the floor even in the design phase before the floor is built.

An analytical model of a standardized tapping machine in time-domain was developed within this project, see *Paper III*. The model was validated for a concrete floor, but it can also be used to simulate the forces on a lightweight wooden floor. The hammer impacts of the tapping machine are made by freefall of the 0.5 kg steel masses on the floor. The mobility of these masses can be assumed to be much higher than the mobility of the floor. Therefore, the machine can be seen as a force source, and the model presented in *Paper III* can be used even for tapping machine impact on a lightweight floor. By performing virtual impact sound evaluation for different floor designs and comparing them with the subjective impact sound evaluations obtained from auralization of walking for the same floor, the correlation between floor design parameters, objective impact sound insulation and the perceived impact sound disturbance for a floor design can be investigated.

### 3 Simulating floor vibrations excited by walking forces

Impact sound transmission of a floor occurs when the floor structure is set into vibration by an impact or a vibrating source, which then results in generation and transmission of sound. Therefore, if the vibrational response of a floor to an impact force excitation can be obtained, the impact sound transmission of that floor can be predicted. However, this also demands a prediction of the radiation. The design tool presented here uses floor vibration signals and simulates the radiation from the floor by an array of loudspeakers mounted in the ceiling of a listening room, and each of them creating the same volume flow as the corresponding part of the vibrating floor.

The vibration velocities of the floor, due to forces, could be obtained by measurements on a floor of interest, as demonstrated later in the text. However, measurements in sufficiently many points might be cumbersome. An alternative could be a modal analysis of a real floor that provides the needed input data (i.e. eigenfrequencies, mode shapes, modal masses and losses) for calculating the vibrational responses of the floor over the surface. However, in both cases it is required that the floor has already been built which would not be in line with the goal to create a virtual design studio. To reach this goal, the floor vibrations should be calculated using analytical models or numerical methods such as FEM. The latter might be preferable when investigating floors with complex structures or floors for which simple plate theory is not applicable.

While measurement data provide the opportunity to investigate a specific floor structure and are restricted to already built floors, using floor models allows for listening to floors in the early design stage. It also allows for carrying out systematic studies in order to investigate the influence of different parameters, such as floor design or material properties on the impact sound insulation and the transmitted sound into the room beneath a floor. In the following, a simple model based on Kirchhoff plate theory is used to calculate the floor vibrations.

#### 3.1 Analytical model of the floor

To calculate the lightweight floor vibrations due to forces, thin rectangular plates with simply-supported edges are assumed (see e.g. [17]). To investigate the influence of floor variations on the perception of the walking sound, three types of lightweight floors are simulated: an isotropic, an orthotropic and a prestressed orthotropic floor.

For an isotropic plate the homogeneous bending wave solution can be written as (see e.g. [17])

$$B\nabla^4\varphi_n(x,y) - m''\omega_n^2\varphi_n(x,y) = 0, \quad (3.1)$$

where  $B$  is the bending stiffness, given in Nm, and  $m''$  is the mass per unit area of the plate, given in kg/m<sup>2</sup>. The eigen-functions that fulfill both the homogeneous bending wave equation and the boundary conditions, assuming a simply-supported structure, are

$$\varphi_n(x,y) = \sin \frac{n_1\pi x}{l_x} \sin \frac{n_2\pi y}{l_y}, \quad (3.2)$$

where  $l_x$  and  $l_y$  are the dimensions of the floor along the horizontal axes  $x$  and  $y$ ,  $n_1$  and  $n_2$  are mode numbers, which are integers greater than or equal to 1, and subscript  $n$  represents double subscripts  $n_1, n_2$ . Using the equations above, the eigenfrequencies for different floor structure models studied here can be obtained.

For the isotropic floor model, The eigenfrequencies were calculated from

$$\omega_n = \sqrt{\frac{B}{m''} \left[ \left( \frac{n_1 \pi}{l_x} \right)^2 + \left( \frac{n_2 \pi}{l_y} \right)^2 \right]}. \quad (3.3)$$

The bending stiffness for an isotropic plate is described as

$$B = \frac{Eh^3}{12(1 - \nu^2)}, \quad (3.4)$$

where  $E$  is the Young's modulus, given in Pa,  $\nu$  is the Poisson's ratio and  $h$  is the thickness of the plate, given in m. The damping is included by a complex stiffness where the loss factor,  $\eta$ , is included in the modulus of elasticity as  $E' = E(1 + j\eta)$ .

The homogeneous bending wave solution for an orthotropic plate with prestress in both directions can be written as

$$B_x \frac{\partial^4 \varphi_n(x, y)}{\partial x^4} + B_y \frac{\partial^4 \varphi_n(x, y)}{\partial y^4} + 2B_{xy} \frac{\partial^4 \varphi_n(x, y)}{\partial x^2 \partial y^2} + T_x \frac{\partial^2 \varphi_n(x, y)}{\partial x^2} + T_y \frac{\partial^2 \varphi_n(x, y)}{\partial y^2} - m'' \omega_n^2 \varphi_n(x, y) = 0, \quad (3.5)$$

where  $T_x$  and  $T_y$  are tensile prestresses in the  $x$  and  $y$  directions, given in N/m. For an orthotropic plate, bending stiffnesses along the length,  $B_x$ , and the width,  $B_y$ , differ, and in addition a mixed bending stiffness,  $B_{xy}$ , has to be considered. While the eigenfunctions for the orthotropic plate do not differ from those found for the isotropic plate [17], the eigenfrequencies do change. The eigenfrequencies for an orthotropic plate without prestress are calculated as

$$\omega_n = \sqrt{\frac{B_x}{m''} \left( \frac{n_1 \pi}{l_x} \right)^2} + \sqrt{\frac{B_y}{m''} \left( \frac{n_2 \pi}{l_y} \right)^2} + \sqrt{\frac{2B_{xy}}{m''} \left( \frac{n_1 \pi}{l_x} \right) \left( \frac{n_2 \pi}{l_y} \right)}, \quad (3.6)$$

where,  $B_{xy}$ , is the mixed or cross bending stiffness, often approximated as  $\sqrt{B_x B_y}$ .

When including the tensile prestresses, e.g. along the  $x$ -direction, the term,  $\sqrt{\frac{T_x}{m''} \left( \frac{n_1 \pi}{l_x} \right)}$ , has to be added to Eq. 3.6.

Once having extracted eigenfrequencies and eigenfunctions, using either a simple model as described above or e.g. with a Finite Element Model (FEM) when required due to the complexity of the floor structure, the modal approach can be utilized to calculate the vibration of the floor due to an excitation. In this case, a force term replaces the zero on the right hand side of the bending wave equation (Eq. 3.5) to obtain the inhomogeneous bending wave equation. By placing the eigenfunctions and eigenfrequencies in the new equation and expanding it, the relation for the plate velocity is obtained, as written below.

$$v(x, y) = \frac{4j\omega}{m'' l_x l_y} \sum_{n=1}^{\infty} \frac{\sin \frac{n_1 \pi x}{l_x} \sin \frac{n_2 \pi y}{l_y}}{\omega_n^2 - \omega^2} \int p(x, y) \sin \frac{n_1 \pi x_0}{l_x} \sin \frac{n_2 \pi y_0}{l_y} dx dy. \quad (3.7)$$

Often it is sufficient to consider the excitation as a point excitation. In the case of a walker this is certainly the case, however it demands not one excitation point, but several for different steps. For a point force excitation,  $p(x, y) = F_0 \delta(x_0, y_0)$  at the location  $x_0, y_0$ , the integral in Eq. 3.7 becomes

simply the value  $F_0$ . The function  $\delta(x_0, y_0)$  given in  $1/m^2$ , is a Dirac delta function with a value 1 at the coordinate  $x_0, y_0$  and a value 0 everywhere else. Eventually the plate velocity at any given point can be calculated as

$$v(x, y) = \frac{4j\omega F_0}{m''l_xl_y} \sum_{n=1}^{\infty} \frac{\sin \frac{n_1\pi x}{l_x} \sin \frac{n_2\pi y}{l_y}}{\omega_n^2 - \omega^2} \sin \frac{n_1\pi x_0}{l_x} \sin \frac{n_2\pi y_0}{l_y}. \quad (3.8)$$

In the case of a walker or tapping machine, the floor is not excited by one point force but by several forces. Therefore, the total velocity of the floor at each receiving position  $(x_r, y_r)$  is calculated by superposing all calculated velocity signals,  $v(x_r, y_r)$ , at that position due to the individual point forces.

The approach used here is only valid for homogenous thin plates. The condition of homogeneity is certainly violated for joist floors. In this case the model could be extended as shown by e.g. in [38, 39] or by using a finite element model. The restriction to thin plates certainly holds for the low-frequency range of interest here.

### 3.2 Application of the model to calculate floor vibrations due to walking

The length and width of the floor were determined based on the dimensions of the ceiling in the listening room as described later in the text. These dimensions were  $L \times W = 4.8 \text{ m} \times 3.73 \text{ m}$ .

The losses of the floor are assumed to be composed of the losses in the material,  $\eta_{material}$ , and the losses due to coupling the floor with the surrounding building elements,  $\eta_{connection}$ .

Praxis shows that using only the material damping leads to too small damping. Especially for relatively lightly damped materials the transmission of vibrational energy to the adjacent structures (e.g. connected walls) is substantially contributing to the overall damping. The loss factor  $\eta_{connection}$  is a frequency-dependent damping term and is determined according to the following equation (see [40])

$$\eta_{connection} = \frac{m''}{485 \cdot \sqrt{f}}. \quad (3.9)$$

To ensure that the modal approach delivers correctly scaled responses, calculated point mobilities were compared with the mobility of a corresponding infinite floor. An example for such a comparison is shown in Figure 3.1. The calculated mobility of e.g. an isotropic infinite plate is given as [17],

$$Y = \frac{1}{8\sqrt{m''B}}. \quad (3.10)$$

The model floor presented in Figure 3.1, was assumed to be isotropic with a thickness of 10 cm, density of  $450 \text{ kg/m}^3$ , and a Young's modulus of 10 GPa. A Poisson's ratio of 0.35 and a material damping 0.2 was applied in the model.

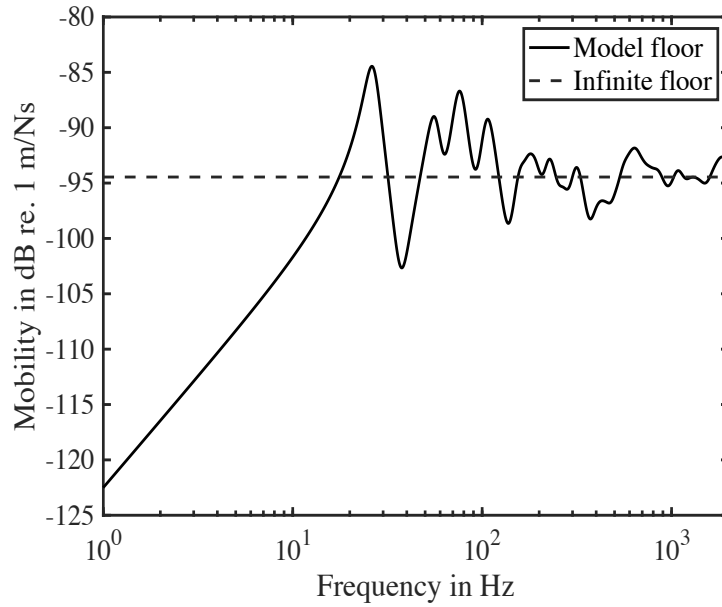


Figure 3.1 Mobility of the model floor at position  $(x,y) = (3.2,2.8)$  m and mobility of an infinite plate with the same material properties.

To calculate vibration velocities of a wooden floor the structure is excited by e.g. walking forces. For this, a sequence of steps is created at different positions and the time sequence for the positions is transformed from time to frequency domain. The resulting forces spectra are superimposed and applied in Eq. 3.8 to calculate the response of the plate.

The velocity on the floor is evaluated at the grid points of a rectangular mesh and is later on used to calculate the volume flow, which has to be reproduced by the loudspeaker array in the ceiling of the listening room.

The spatial resolution of the mesh cells was chosen to be about  $5 \times 5 \text{ cm}^2$ . As the contact between a foot and the floor takes place mainly in the heel and ball regions of the foot, the impact forces corresponding to these two regions could be taken in the model separately. However, the distance between the heel and ball of the foot are quite small compared with the wavelengths in the frequency range of interest in our experiments ( $f \leq 120 \text{ Hz}$ ). Thus, the entire foot impact could be assumed as one point force, and instead of spatially separating the heel and the ball forces for each step, the superposition of these forces was used as the footstep force in the calculations. Figure 3.2 shows the calculated floor vibrations generated by two consecutive steps when each footstep force is represented by separate heel and ball forces at two different points 15 cm apart, compared with when the superposition of these forces for each step is applied at one point in the middle of the pre-defined heel and ball positions.



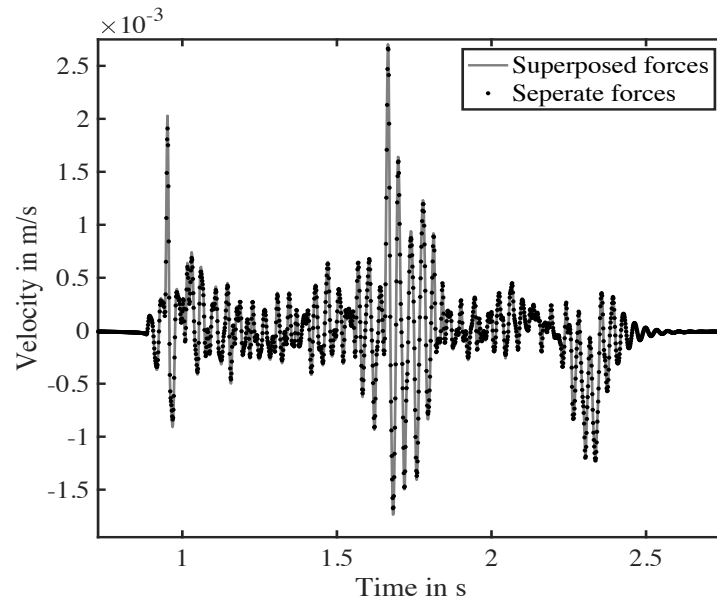


Figure 3.2 Calculated velocity of the floor at position  $(x,y) = (2.14,1.17)$  m, when two point forces, 15 cm apart, represent one footstep, versus using the superposition of the heel and ball forces at one point in the middle of the heel and the ball positions.

In the simulations of walking paths, whenever the walker strode along a straight line, a 10 cm gait base, also known as the stride width (the lateral distance between the mid-lines of the two feet during walking), was used. In consecutive steps, the step length that was applied in the model, was 60 cm. Since the heel and ball forces were replaced by a single point force, the gait angle,  $\theta$ , between the axis of the foot and direction of walking, was not of any interest in the model.

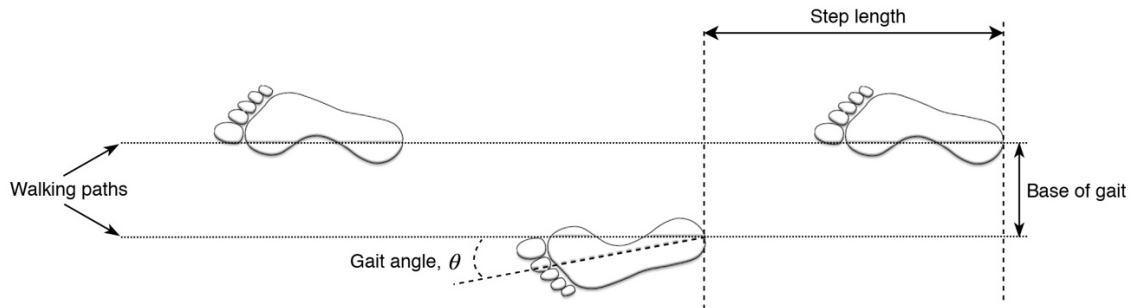


Figure 3.3 Walking path parameters.

Five walking paths were used for impact excitation modelling in this thesis. The paths and their corresponding step sequence are as shown in Figure 3.4.

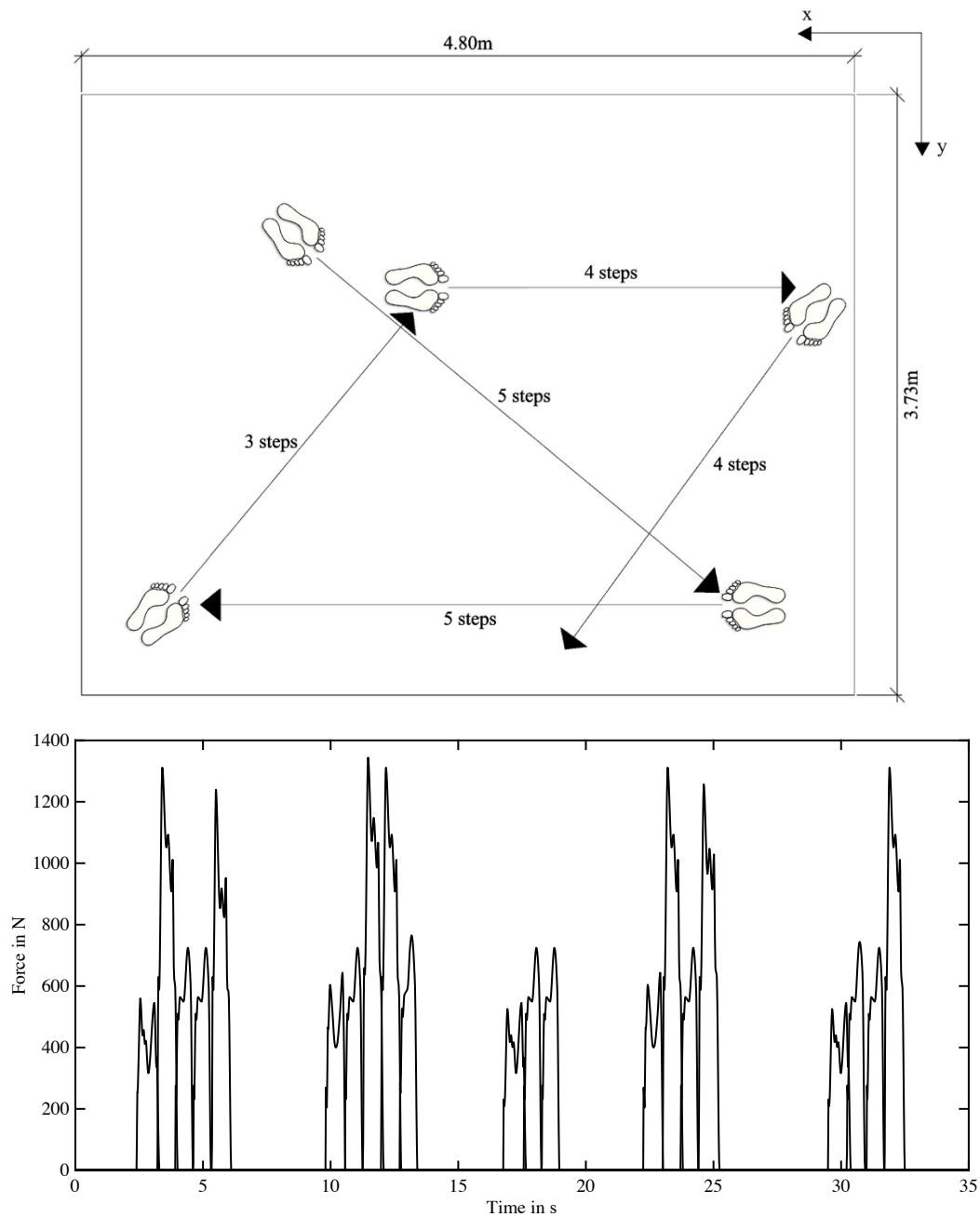


Figure 3.4 Walking paths (top) and walking force sequence (bottom) used for modelling footstep impacts.

An example of the vibration velocity resulting from exciting the model floor (same as in Figure 3.1) with the footstep sequences presented in Figure 3.4 is shown in Figure 3.5. As a comparison, vibration velocities measured on a real wooden floor excited by a sequence of footsteps similar to that of the model is also shown in the figure. The results show that the simulated floor vibrations are at least in the same magnitude order as the real floor vibrations. In all walking sound simulations presented in this thesis, the same step sequence and time variations between the consecutive steps, as shown in Figure 3.5 were used.

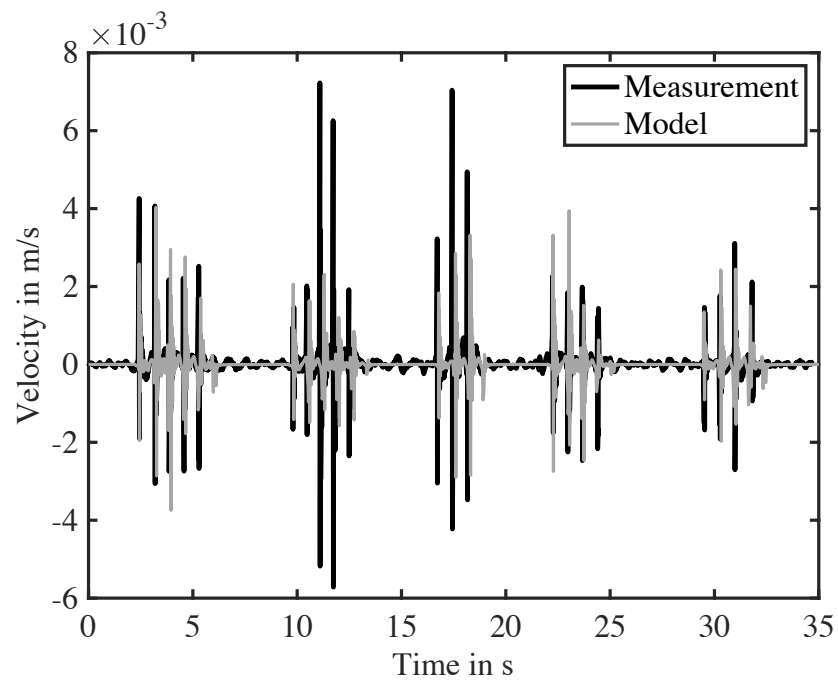


Figure 3.5 Floor vibrations at position  $(x, y) = (2.88, 1.41)$  m due to the five walking sequences.



## 4 Impact force auralization

As the final part of the virtual design, an auralization tool is needed. This chapter describes the laboratory built as a virtual living room for auralization of impact sounds. Moreover, the procedure for simulating the floor vibrations with the sound reproduction system in the lab is elaborated on.

### 4.1 Design of the listening lab

Chalmers listening laboratory for auralization of impact sound is constructed within a larger room with walls and ceiling of thick ( $\sim 20$  cm) concrete and dimensions  $L \times W \times H = 5.5 \times 4.8 \times 3.6$  m<sup>3</sup>. The large room was previously used as a part of a horizontal sound transmission measurement lab, and has high acoustic insulation from the surrounding. The dimensions of the listening lab built inside are  $L \times W \times H = 4.80 \times 3.73 \times 3.52$  m<sup>3</sup>. The listening lab is sized and decorated so that it resembles a living room, see Figure 4.1.



Figure 4.1 Chalmers listening laboratory for auralization of impact sound.

The sound reproduction system of the listening lab consists of twenty Genelec 8020B loudspeakers, which cover mid and high frequency ranges between 66 Hz and 20 kHz, and four Neumann KH805 active subwoofers with a frequency range of 18 to 300 Hz. An Orion32 AD/DA convertor is used to transform the computer-generated digital signals to analog signals for the loudspeakers. All the loudspeakers and connecting cables in the listening lab are hidden behind a suspended acoustically transparent ceiling, so that their visual effect does not influence the perception of the sound in the room. The suspended ceiling is installed at the height of 2.46 m from the floor, which makes the visible height of the room smaller than its actual height, and closer to the ceiling height of common apartments in Sweden. The ceiling tiles of the suspended ceiling are made of a thin woven cotton fabric with a density of 0.265 kg/m<sup>2</sup>, which can be assumed as acoustically transparent at the low frequencies of interest in our experiments.

The subwoofers are mounted close to the concrete ceiling of the lab, near the corners, with the diaphragm center approximately 36 cm away from the ceiling. The mid-to-high frequency range

loudspeakers are installed 80 cm below the concrete ceiling. This position might not be optimal from an acoustic point of view due to the relatively large distance to the reflecting ceiling above. It might lead to constructive or destructive interference between loudspeaker and image source. However, for most of the sounds investigated here, the mid-to-high frequency range loudspeakers are of minor importance for the overall sound levels. Initial listening gave the conclusion that they are mainly important for localization (of walkers or of other sources).

As the loudspeakers should represent a vibrating ceiling, it would have been better to have the mid-to-high frequency range loudspeakers mounted directly in front of the reflecting ceiling. This might be corrected in the future.

## 4.2 Simulating floor vibrations with the sound reproduction system

To auralize the walking sound, all of the 20 mid-to-high frequency range loudspeakers and 4 subwoofers, mounted in the ceiling of the lab, were used. The mid-to-high frequency range loudspeaker grid has a  $5 \times 4$  arrangement along the length and the width of the room respectively, see Figure 4.2.

A digital crossover filter was used to separate the low frequencies from the high frequencies. Tailor-made hamming filters were applied for this purpose. The velocity signals for subwoofers were low-pass filtered at a cut-off frequency of 70 Hz, and the mid-to-high frequency range loudspeaker signals were high-pass filtered at 70 Hz.

In order to reconstruct the floor vibrations with the loudspeaker system, the floor mesh had to be mapped onto the mid-to-high frequency range loudspeaker grid as well as to the subwoofer grid. For each of the grids, this was made by first dividing the floor into the same number of surface areas as the number of loudspeakers, and then calculating the total volume velocity generated by all the mesh cells in each area. The volume velocity generated by each loudspeaker should be equal to the calculated volume velocity of its corresponding area. By dividing the total volume velocity of the area by the corresponding surface area of the loudspeaker diaphragm,  $S_{diaphragm}$ , the equivalent velocity signal to be generated by the loudspeaker could be obtained as described below.

$$v_{loudspeaker} = \frac{S_{cell} \frac{\sum_{i=1}^I \sum_{j=1}^J v_{ij}}{N_{IJ}}}{S_{diaphragm}}. \quad (4.1)$$

Here,  $S_{cell}$  is the surface area of each rectangular mesh cell used in the floor calculations,  $i$  and  $j$  are the indices determining the row and column of the cell in the area allocated to each loudspeaker, and  $v_{ij}$  is the velocity of the cell obtained from averaging the velocity signals corresponding to the four node points of each cell. The map of all mid-to-high frequency range loudspeaker locations as well as the areas of the floor allocated to each loudspeaker are shown in Figure 4.2. To map the model floor onto the subwoofer grid, the floor was divided into four equally large rectangular pieces.

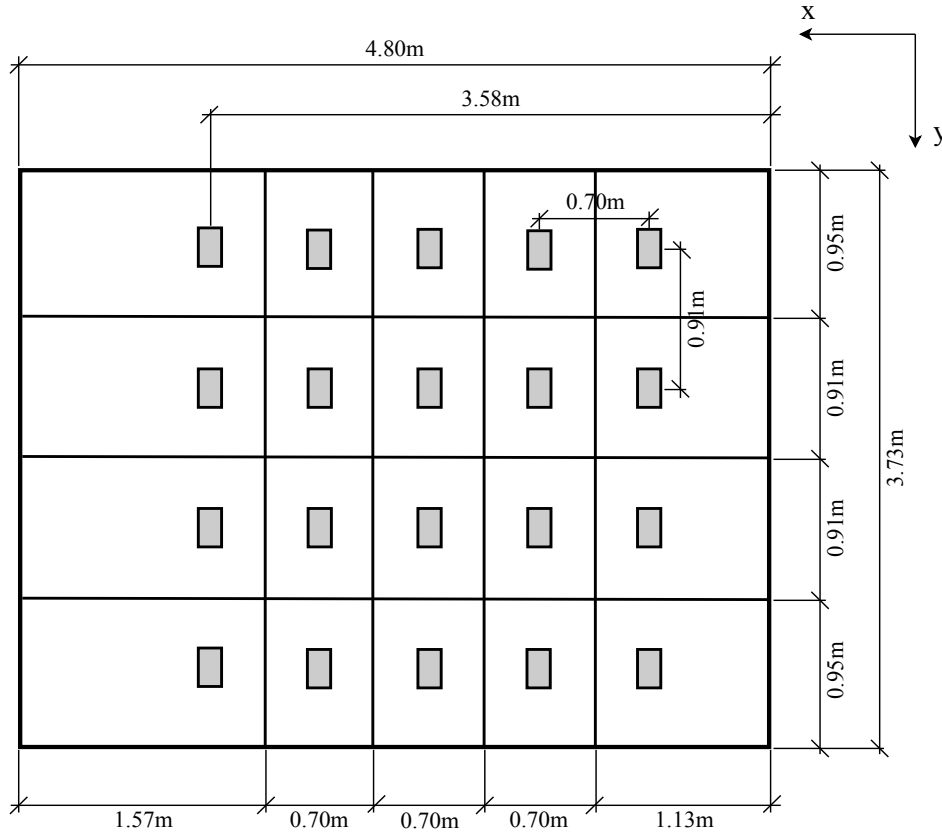


Figure 4.2 The model floor mapped onto the mid-to-high frequency range loudspeaker grid.

### 4.3 Accounting for loudspeaker internal transfer function

Every loudspeaker has an internal filtering effect on the input signals when converting the input voltage into vibration of the diaphragm that eventually generate sound. This internal transfer function results from different electrical, mechanical and acoustical mechanisms that convert a digital electric signal into mechanical vibrations leading to sound radiation.

When simulating floor vibrations by loudspeakers, to obtain the expected equivalent loudspeaker velocity,  $v_{loudspeaker}$ , one needs to compensate for the internal transfer function of the loudspeaker in the input signal. In order to do this, the transfer function between the input voltage and the output vibrations of the diaphragm has been measured for both types of loudspeakers. Afterwards, the inverse of the identified transfer functions is transformed to an impulse response function which is then convolved with the required (calculated) signals in order to obtain the voltage signals to be applied to each loudspeaker.

The internal impulse responses of the mid-to-high frequency range loudspeakers and the subwoofers were measured using a broadband voltage signal as input, and the velocity of the diaphragm as output. The velocities were measured using a laser doppler vibrometer. The inverse impulse responses were calculated using the LMS filter identification method [41]. In order to increase the stability of the inverse impulse response functions estimated by the LMS algorithm, velocities at multiple points on the diaphragm were measured and used in the calculation.

Two practical challenges were faced when measuring the transfer functions of the loudspeaker:

- 1- At some positions on the diaphragm, the measured transfer functions in frequency domain (frequency response functions), showed lower amplitudes than other positions in their vicinity, although their transfer function curves had the same slope and general shape. This could be due to positioning of the laser beam on a curve or a slope of the membrane surface, which might give a different velocity component along the direction that is measured by the laser than the points that are on the flatter parts of the diaphragm.
- 2- The loudspeaker grille can sometimes stop the laser beam from being solely focused on the diaphragm, and this causes appearance of noise in the signal, and affects the accuracy of the data.

To overcome these uncertainties, the measurement points with noisy signals or low frequency response functions (FRF) amplitudes compared to other points were dismissed, and an average of FRFs at the rest of the measurement points was used as the transfer function of the loudspeakers. The resulting FRF curve was then applied to estimate the inverse impulse response of the loudspeakers in an iterative process using LMS algorithm. Figure 4.3 shows the average transfer functions obtained from the measurements.

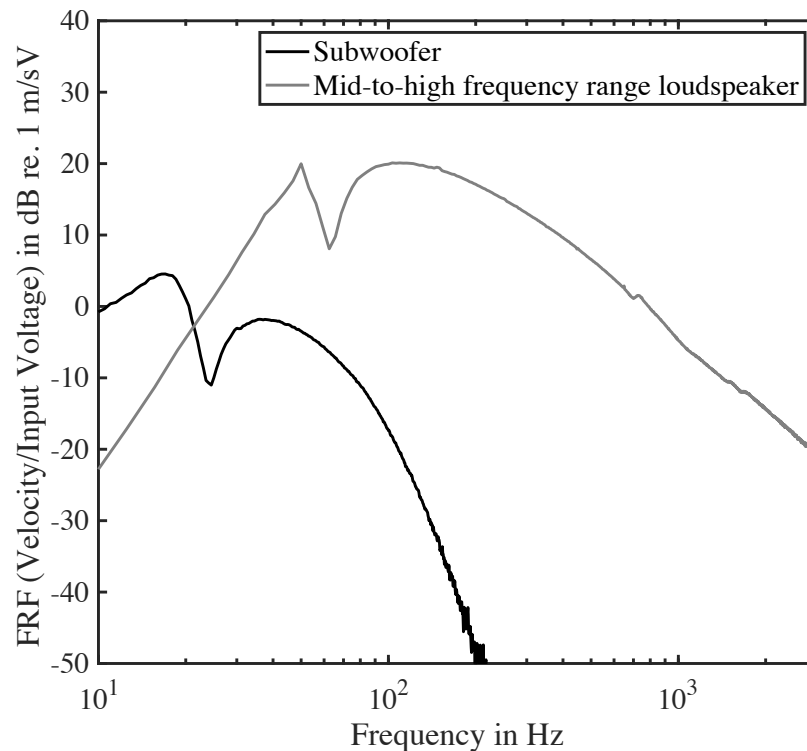


Figure 4.3 Average frequency response functions of the mid-to-high frequency range loudspeakers and subwoofers obtained from dividing the diaphragm velocity by the input voltage of the loudspeakers.

To obtain the transfer function of the mid-to-high frequency range loudspeakers, the measurements were only made on the bass cone driver, since the dome tweeter become effective at frequencies above 3 kHz [42], which is out of the range of interest here.

All the loudspeakers in the listening lab are ported, which means that there is a hole cut into the loudspeaker enclosure that is connected to a pipe with an open end inside the loudspeaker box. The port is used to increase the efficiency of the system at low frequencies by using the sound from behind



the diaphragm. The port is made to be effective mainly close to the lowest frequency limit of the loudspeakers. Therefore, when the lowest frequency range of the loudspeakers are used, as was the case in this thesis, the effect of loudspeaker port has to be taken into account for calculating the FRFs of the loudspeakers. The procedure is described as follows.

For a ported loudspeaker, the total sound pressure at distance  $r$  from the loudspeaker can be obtained as [43]

$$p_{total} = p_{diaphragm} + p_{port} = \frac{j\omega\rho_0}{4\pi r} (U_{diaphragm}e^{-jkr_d} - U_{port}e^{-jkr_p}), \quad (4.2)$$

where,  $p$  is the sound pressure,  $\omega$  is the angular frequency,  $\rho_0$  is the density of air,  $U$  is the complex amplitude of the volume velocity, and  $r_d$  and  $r_p$  are the distances from the point of observation to the diaphragm and the port, respectively, where  $r$  is the average distance of the two. The negative sign used in the equation above is because of the opposite directions of air movement for the diaphragm and the port, which means that when the diaphragm moves inwards, the air from the port moves outward.

The total volume velocity generated by the loudspeaker can be obtained as the superposition of volume velocity of the vibrating diaphragm and volume velocity of the port.

$$U_{total} = U_{diaphragm} - U_{port}, \quad (4.3)$$

Using the total volume velocity of the loudspeaker, the transfer function of the ported loudspeakers could be calculated. In order to obtain the volume velocity of the port, the volume of the air inside the loudspeaker enclosure and the port damping have to be known. These are design parameters which were not included in the users' manual of the loudspeaker and could not be accessed even after contacting the manufacturers. Therefore, in the FRF calculations, estimates of the values of the needed parameters were applied, based on the effective frequency range of the loudspeakers as well as their physical dimensions. In the calculations, the ratio of *volume velocity* to *voltage* was used as the transfer function of the loudspeakers. Figure 4.4 shows the volume velocity curves and final transfer functions of the loudspeakers.

For auralizing the walking sounds, the inverse of the loudspeaker transfer functions in time domain (IRs) were first calculated using the FRFs presented in Figure 4.4. The inverse IRs were then convolved with the calculated equivalent volume velocity signal for each loudspeaker in order to obtain the input voltage signal for the loudspeaker. The equivalent volume velocities were obtained based on the equivalent velocity calculated for the floor area.

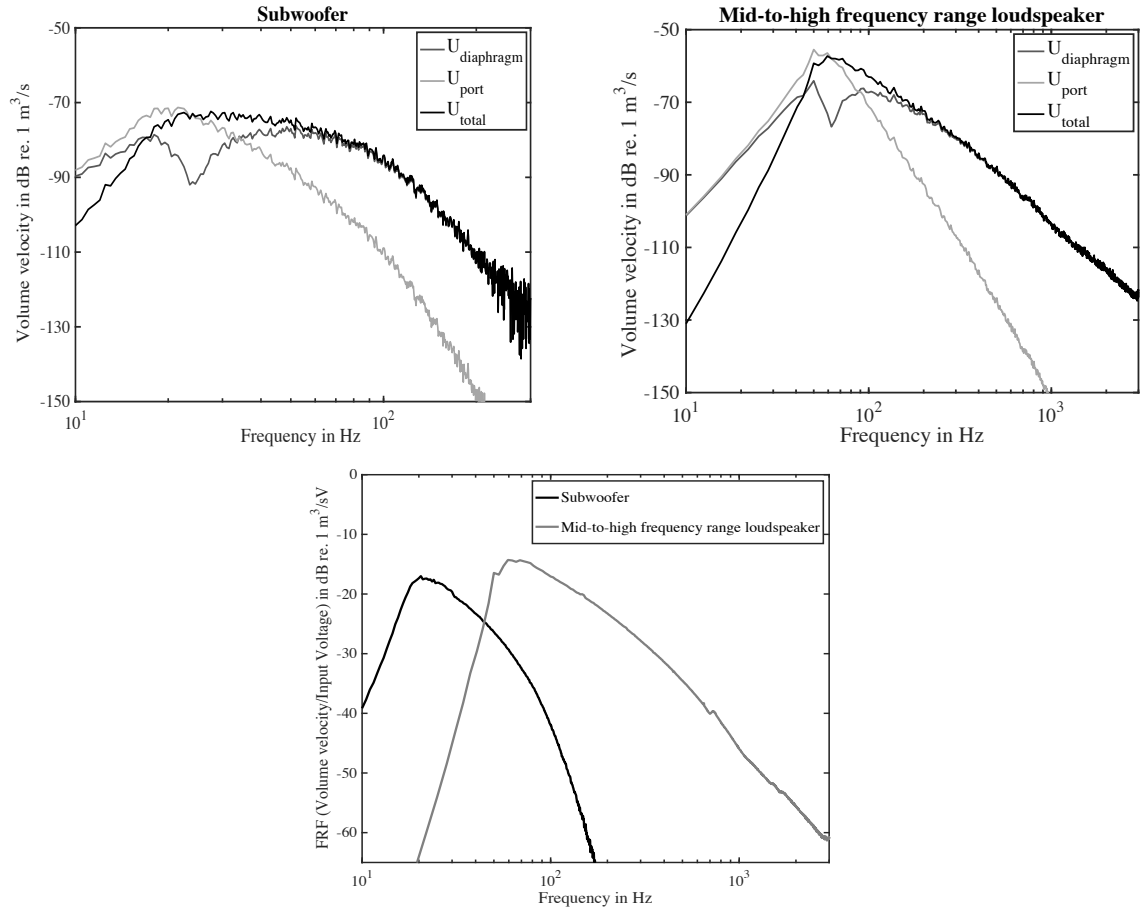


Figure 4.4 Volume velocities (top) and frequency response functions of the loudspeakers (bottom).

## 4.4 Comparison with the field measurements

To demonstrate, and as an attempt to validate the entire auralization chain, the auralized impact sound induced by walking on a real floor was compared with an in-situ measured transmitted walking sound from the same floor.

The measurements were conducted in a wooden two-storey test house at RISE Research Institutes of Sweden. The building is erected as a single-family house, see *Appendix A*. The receiving room is used as a conference room and is furnished with a television screen, a large wooden rectangular conference table and ten wooden chairs with cushioning only on the inner side. The chair cushions are the only surfaces of the room with significant absorption.

The test floor was without furniture except for a small empty bookshelf that was placed next to the wall along the length of the room. The floor velocities, required for auralization, were acquired by measuring the ceiling vibrations in the receiving room underneath when someone walked on the floor above.

The test structure was a joist floor with the dimensions  $L \times W = 4.74 \times 3.73 \text{ m}^2$ , which is very similar to the dimensions of the ceiling in the listening lab. The bare floor consisted of 22 mm thick chipboards screwed to the floor joists. Wooden parquet was used as floor covering. Between the chipboards and the floor covering, a 30 mm layer of plastic foam was installed that held the floor heating pipes. The cross-section area of the joists was  $L \times W = 45 \times 220 \text{ mm}^2$ , and the distance

between them was 600 mm. The total thickness of the floor structure was 600 mm, and the gap between the top plate and the ceiling of the room below was filled with 450 mm of isolating material. For the ceiling, 13 mm gypsum boards were used (see *Appendix A*).

For the vibration measurements, twenty accelerometers were mounted on the ceiling of the receiving room. The sensors were attached at the same positions as the center point of the loudspeakers in the listening lab, see Figure 4.5. For reproduction of the walking sound from the measurements, first, velocity signals at the measurement positions were calculated by time-integrating the measured accelerations. Velocities at all node points in the floor mesh, as defined in the simulations, were then calculated by a two-dimensional linear interpolation of the measured velocity signals. This was made for a more accurate calculation of the total volume velocity of the floor areas represented by the loudspeakers. After calculating the node velocities for the entire floor, the same procedures for calculating equivalent loudspeaker membrane velocities and calibrating the auralization chain, as explained in the Sections 4.2 and 4.3, were used to obtain the output signals for the loudspeakers. The auralized walking sound in the lab was then measured at the same position as was done in situ. Figure 4.5 shows the comparison between the auralized and in-situ sound pressure levels. The spectra are plotted for 5 consecutive steps. A 1.4 Hz line spectrum appears since this was the average frequency of the steps. The curves show a good agreement in the frequency range from approximately 20 Hz up to about 120 Hz. Below 18 Hz the comparison is not valid because of the low-frequency limit of the subwoofers. The deviation of the curves above 120 Hz could be explained by the presence of sound absorbing furniture and surfaces such as the sofa and the curtains in the listening lab, while in situ the majority of the surfaces were hard with very little absorption. Although there is a fair agreement between the measurement and simulation, further investigation of the differences would be needed, but could not be carried out in the time frame of this thesis. Despite this, one can conclude that the auralization procedure at least gives the same order of sound pressure levels in the listening room.

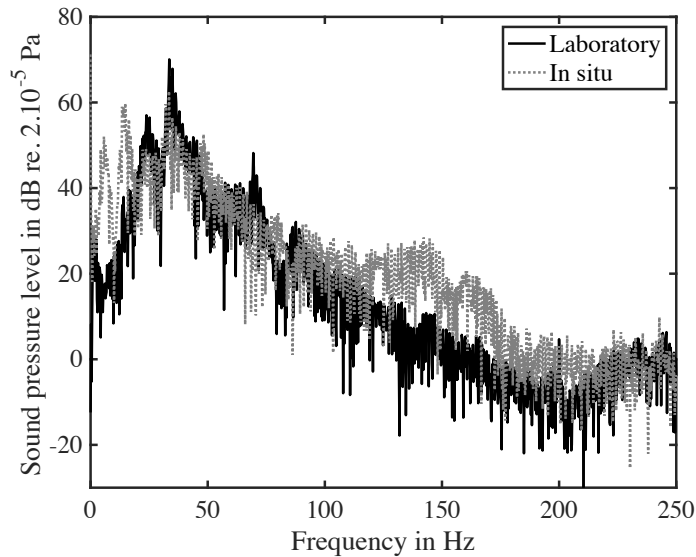


Figure 4.5 Sound pressure levels measured at the coordinate  $(x, y, z) = (1.85, 0.8, 1.2)$  m in the room.  $L_{p, in situ} = 74.3$  dB and  $L_{p, laboratory} = 76.6$  dB.



## 5 Listening test

By applying the virtual design tool presented here, impact sound generated by walking on different floors could be auralized. In the following, the functioning of the tool is demonstrated by investigating different sounds in a listening test. The demonstration focuses on the ability of the virtual design tool to reproduce variations in the walking sound that can be associated with changes in the floor design.

The listening tests were performed also with the aim of evaluating the plausibility of the auralized sounds. The plausibility of the sounds was tested both by asking the test subjects about the naturalness of the walking sounds and by investigating how reasonable the results from the listening test are.

A categorical scaling test was used for subjective evaluation of the sounds. To investigate the correlation between the floor design and subjective responses, the terms that were applied for evaluation of the walking sound corresponded to subjective interpretation of overall performance or different mechanical properties of the floor.

The results from the listening test are also related to impact sound insulation of the floors, calculated using the measured sound pressure levels inside the listening room due to a virtual tapping machine.

Section 5.1 presents the different floors investigated in this study, and Section 5.2 presents the procedure and results of the virtual impact sound measurements of the floor objects. Section 5.3 explains how the listening test was carried out. Section 5.4 finally presents and discusses the results.

### 5.1 Floor objects

The material properties of the floor models that are used in the auralization are presented in Table 5.1. The thickness of the floor in all models is 10 cm. The material properties of the orthotropic floor model M1 are chosen based on the properties provided for a typical CLT floor in the literature, e.g. in [44]. Different parameters such as Young's modulus, density and damping of the floor are varied in different models. The prestressed floor model is used to investigate the impacts of stiffening the floor and moving up the first floor resonances on the perceived annoyance by walking sound. In model M10, properties of lightweight concrete, given in e.g. [45], are used for sound perception comparison.

It should be pointed out that the material properties of all the floor models were selected in a way that the resulting walking sounds become audible and clear, which corresponds to a poor impact sound insulation performance. However, the aim of this study is not to suggest a good floor design, but to demonstrate and investigate the capabilities of the design tool.

In addition to the model floors, the floor vibrations measured in-situ were used for auralization of a real case of walking sound as the reference for testing naturalness of the walking sounds generated by the design tool. Therefore, 11 floor designs in total were applied in the listening tests. Figure 5.1 shows the (calculated or measured) driving point mobility for these floors.

Table 5.1 Material properties of the model floors.

Floor model	$\rho$ , kg/m <sup>3</sup>	$\nu$	$E$ , GPa		$T_x$ , kN/m	$\eta_{int}$
			$E_x$	$E_y$		
M1	450	0.35	10	0.37	-	0.2
M2	450	0.35	7.5	0.37	-	0.2
M3	450	0.35	5	0.37	-	0.2
M4	450	0.35	10	0.37	5000	0.2
M5	350	0.35	10	0.37	-	0.2
M6	250	0.35	10	0.37	-	0.2
M7	450	0.35	10	0.37	-	0.3
M8	450	0.35	10	0.37	-	0.1
M9	450	0.35	10		-	0.2
M10	1600	0.2	14		-	0.07

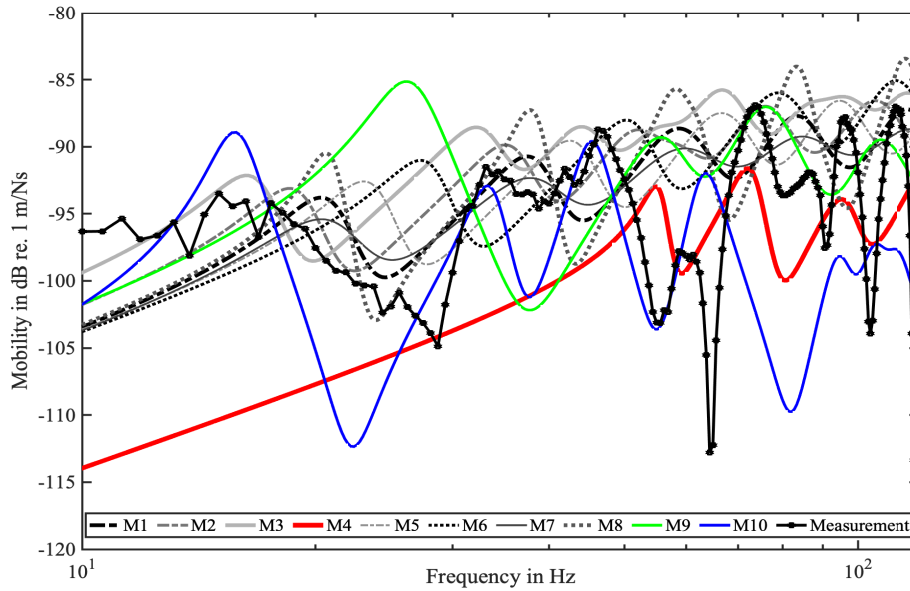


Figure 5.1 Driving point mobility of the floors at position  $(x, y) = (0.8, 3)$  m.

Sound pressure levels of the auralized walking sound at listener's position,  $(x, y, z) = (1.85, 0.8, 1.1)$  m, for each test floor were measured prior to the listening tests. The results are shown in Table 5.2.

Table 5.2 Equivalent SPLs at listener's position.

Floor	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	Measurement
$L_p$ , dB	78.6	77.4	78.5	58.6	81.2	79.7	76.7	81.1	76.9	69.7	74.6

Listening to the impact sound generated by walking on the floor in situ showed that the measured floor has a poor impact sound insulation, which was later also proven by measuring the impact sound insulation of the floor, see Section 5.2. The poor impact sound insulation of the floor can be explained by the fact that it belongs to a single-family (test) house, for which there is no strict sound insulation regulation, so the floor is built without considering acoustic performance. Accordingly, the auralized walking sound for this floor was also perceived as very loud and it raised a concern that the loudness of the sound might affect the perception of plausibility of the stimuli. Therefore, to test this assumption, two extra sound samples were added to the listening tests, which were generated by reducing the calculated output voltage of the loudspeakers for the in-situ floor by a factor 2 (-6 dB) and 3 (-9 dB). For ease of reading, from here on, we denote the real floor as M11, and the two sound samples with 6 and 9 dB reduction, as M12 and M13, respectively.

## 5.2 Standardized impact sound insulation measurements using the virtual design tool

To provide an objective measure of impact sound insulation for the floor objects, the impact sound pressure levels for all floor samples were measured and evaluated according to ISO 16283-2 and ISO 717 standards [13, 14]. This was made for model floors (M1 to M10) by simulating the impact forces of a standard tapping machine on the floor and auralizing the tapping machine sound using the virtual design tool. The resulting sound pressure levels in the listening lab were then measured and evaluated according to the ISO standards to obtain the single-number quantity of impact sound insulation of the floors.

To simulate the hammer impacts, a sequence of impact forces was generated for every tapping machine position. Impact excitations for totally 6 virtual tapping machine positions were simulated for each floor. The force signals for the hammer impacts were obtained from the previous measurements of tapping machine forces using the LMS method, presented in *Paper I*. For each hammer, five sets of measured forces were available, which were used randomly to simulate the slight variations between the impacts at each rotation of the camshaft. The sequence of hammer drops was 1, 4, 2, 5, 3, where hammer 1 is farthest from the tapping machine engine. This hammering sequence is the same as the sequence of the impacts in the Norsonic type Nor-211A tapping machine that provided the force data. The time between the successive impacts of the hammers were randomly varied (with uniform distribution) within the permitted range of the standard, which is  $100 \pm 5$  ms. For each tapping machine position, a 30 second long sequence of forces was generated.

The generated force sequences for each floor were applied in the floor models, using the procedure presented in Chapter 3, to obtain the vibration velocities of the floor. The floor vibrations induced by tapping machine impacts on the real floor (M11), were obtained directly from measurements, using accelerometers attached to the ceiling of the receiving room, as explained in Section 4.4.

Finally, the tapping machine sounds were auralized in a similar procedure as the walking sounds, according to the steps presented in Chapter 4. A band-pass filter was used for filtering the mid-to-high frequency range loudspeaker signals with a passband range of 70–2000 Hz.

The energy-average impact sound pressure level,  $L_i$ , was measured for each tapping machine position using two fixed microphone positions in the room, as described in ISO 16283-2. The standardized impact sound pressure level in the listening room was calculated in third octave bands in the frequency range of 100–1600 Hz as below.

$$L'_{nT} = 10 \log \left( \frac{1}{m} \sum_{i=1}^m 10^{\frac{L'_{nT,i}}{10}} \right), \quad (5.1)$$

where  $m$  is the number of tapping machine positions, and  $L'_{nT,i}$  is the standardized impact sound pressure level for the tapping machine position  $i$ , obtained from the following equation,

$$L'_{nT,i} = L_i - 10 \log \frac{T}{T_0}, \quad (5.2)$$

where  $T$  is the reverberation time of the receiving room and  $T_0$  is the reference reverberation time,  $T_0 = 0.5$  s.

Although the impact sound insulation rating according to the ISO standard demands measurement of impact sound pressure levels at least up to the 3150 Hz third octave band, the upper frequency limit of the measured hammer forces were 2000 Hz, which did not allow for extending the evaluations to frequencies above the 1600 Hz third octave band. However, the missing high frequency bands are not expected to influence the impact sound insulation rating because of the generally relatively high impact sound insulation of wooden floors at high frequencies.

The weighted standardized impact sound pressure levels,  $L'_{nT,w}$ , for each floor was determined according to the procedure described in ISO 717-2. Furthermore, two spectrum adaptation terms  $C_{I,50-2500}$  and  $C_{I,20-2500}$  were calculated according to ISO 717-2 and the Swedish standard SS 25267:2015, respectively, taking into account the performance of mainly lightweight floors at low frequencies down to 50 Hz and 20 Hz.

The weighted standardized impact sound pressure levels of the lightweight floor objects and the spectrum adaptation terms are presented in Table 5.3.



Table 5.3 Weighted standardized impact sound pressure levels of the floor objects.

Floor	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
$L'_{nT,w}$ , dB	60	60	59	59	62	65	58	62	59	51	68
$C_{I,50-2500}$	11	13	13	13	12	12	12	11	11	16	4
$C_{I,20-2500}$	25	26	24	14	23	22	25	27	22	26	13

### 5.3 Design of the listening test

For subjective evaluation of the walking sound on different floors semantic differentials [46] were used. The adjectives used in the semantic scales were selected in association with various properties of the sample floors. The semantic differentials were adapted so that they could reflect the intended physical properties of the floor. Therefore, both bipolar and artificial bipolar semantic scales were used in the test. For example, for evaluation of loudness a bipolar scale using the adjectives ‘Low’ and ‘High’ was used, while for example for annoyance, an artificial bipolar scale ranging between ‘Not annoying’ and ‘Very annoying’ was used. The rating scales consisted of 7 equidistant steps, ranging from 1 to 7. A list of the attributes as well as their range are presented in Table 5.4. Attributes such as distinctness and thumping have been used in the literature [47] to describe the perceived impression of impact sound from walking on different floor structures.

Table 5.4 List of attributes used in the listening test and their range.

Attribute	Range	
Loudness	Low	High
Distinctness	Not distinct	Very distinct
Thumping	Not thumping	Very thumping
Reverberation	Not reverberant	Very reverberant
Annoyance	Not annoying	Very annoying
Naturalness (plausibility)	Artificial	Natural

In the listening test, only footstep sounds generated by walking barefoot on a lightweight floor were used. The motivation is that barefoot walking has shown to have more audible low-frequency content and is perceived more annoying than the footstep sounds generated by walking with shoes [12].

The selected listener’s sitting position was only representative of a real-life case, with the listener sitting on the sofa in front of the TV. This means that selection of the listening position was not based on the flatness of the room response in that position. The only consideration for the sitting position was to be away from the center and the corners of the room, where the probability of exposure to the minimum or the maximum sound pressure level in the room is higher.

Twenty subjects (16 male, 4 female) participated in the experiment. Their age varied between 23 and 40 years with an average of 28.8 years. The majority of participants (17 out of 20) were students and staff at the Applied Acoustic division at Chalmers University of Technology. The subjects had

different nationalities and were from 3 different continents (America, Europe and Asia) with a majority from Europe. Nearly half the test participants (9 out of 20) reported having lived in buildings with wooden floors, all of which were well familiar with hearing their neighbors upstairs walking, and 7 of them reported being regularly disturbed by the walking sound. The rest of the subjects reported having lived in buildings with concrete floors. Of these 11, 5 stated to have no experience of hearing impact sound from walking. In total, 7 subjects reported to be annoyed by the impact sound generated by walking at home, all of which lived in buildings with wooden floors.

The listening test was performed with one participant at a time. The subjects were informed in advance about the procedure of the test and that they were going to evaluate walking sounds. They were also told that they are free to leave the room at any time and for any reason during the experiment or withdraw from the experiment if they wish. The results were anonymized before stored for later evaluations.

The instructions of the test were presented in a written format. Also, the test leader attended the training session to answer potential questions. Before the start of a test, the subjects first evaluated three sounds, M5, M10 and M11, as training, in order to get familiar with the test procedure and the content of the sounds. The 13 test sounds, M1–M13, were then presented to the participants in an individually randomized order. Each sound sample was played twice, which means that each participant assessed 26 sound samples in total. The duration of each sound sample was 35 s, and they were played in a loop with the possibility for the participant to pause the sound if they wanted.

No information about the loudness range was given to the participants in advance, because they were asked to judge the sounds based on their own perception of a real-life case at home. The tests lasted 40 minutes on average.

The test instructions and an example of the test interface are presented in *Appendix B*.

## 5.4 Results and discussion

Figure 5.2 summarizes the listening test results for all the participants and all the sound samples as boxplots. The horizontal line inside the boxes shows the median (50th percentile) value, and the lower and upper edges of the boxes show the 25th and 75th percentiles, respectively. The whiskers show the outmost ratings that fall in the lower and upper range of 1.5 times the interquartile range (1.5 IQR). Any rating outside the whiskers is shown as an outlier and is displayed as “+”.

For almost all the sounds in all attribute categories, the subjective responses are spread over the entire rating range. However, depending on the attribute and the floor model, the distribution of the answers differs. The data are analyzed using mean and regression analysis as well as a combination of one-way ANOVA and t-test analysis in order to investigate the statistical significance of the results.

Among the 6 categories, the perceived loudness shows the most variation for the different floors. Analysis of the loudness data shows that for every floor there are at least two floors that are judged as significantly different in loudness. The judgements in the annoyance category appear to follow the same pattern as the loudness data implying that there is a correlation between these data, as expected. However, there are less differences in the perceived annoyance than in the loudness. The correlation between different categories is further discussed in the following sections.

The minimum variations among the categories are obtained in naturalness, with no significant difference between any of the sound samples (used significance level is 0.01). The average ratings for all model floors in this category are between 4.2 and 5.3 (out of 7), while for the three real floor examples the averages are between 4.4 and 5.3. This means that the test subjects, on average, could not identify any significant difference between the impact sound generated by simulations and the sound generated by using measurement data on a real floor.

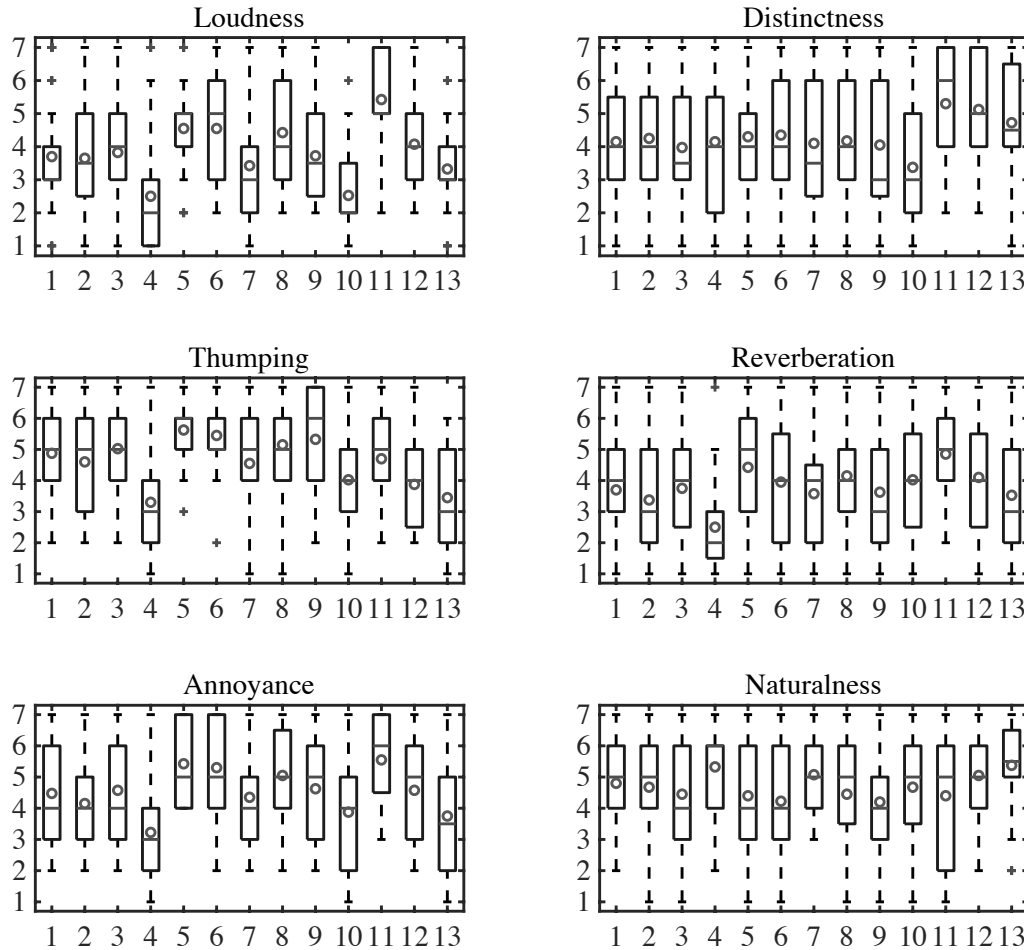


Figure 5.2 Listening test results for all the participants and all sound samples. The horizontal axis represents the floor sample, and the vertical axis shows the rating values. The circles show the mean values of the data for each sound sample in each category.

Another category with small variations is the distinctness. The distinctness that was described for the subjects as distinguishability and clarity of the successive footsteps, has received an average rating between 4 and 5.3 for nearly all samples. The only sound with significant difference relative to the others is M10, with an average rating of 3.4. The significant difference is only between this sound and the two real floor examples M11 ( $p = 0.0002$ ) and M12 ( $p = 0.001$ ). Another aspect of the distinctness ratings is the long whiskers the boxplots, which spread along the entire range for 11 out of 13 sounds in this category. This means that there is not a complete consensus among the subjects about the distinctness of the walking sounds in general. This could be due to various reasons. It might imply that different subjects had different understanding regarding the meaning of distinctness, but also it could mean that this attribute is in general difficult to evaluate for the given samples due to the low frequency content of the sounds. For example, the sound from walking with shoes that contains higher

frequencies is expected to receive a higher more homogeneous distinctness rating than the barefoot walking sounds.

### 5.3.1 Effect of familiarity with the walking sound

To investigate whether familiarity with walking sound in buildings and the type of floor the participants are used to influence the perception of sound, the participants were divided into different categories; group 1: subjects who had experience with walking sound on wooden floors (9 persons), group 2: subjects with experience of walking sound on concrete floors (6 persons), and group 3: subjects who had never heard the impact sound generated by walking sound (5 persons).

To investigate how significant is the effect of prior experience on subjects' judgements, a comparison between all the population groups is presented in Figure 5.3. The curve 'All' represents the results for all participants, while the 'Wood' and 'Concrete' curves refer to the groups 1 and 2, and the unexperienced test subjects in group 3 are represented by 'No Experience' curves.

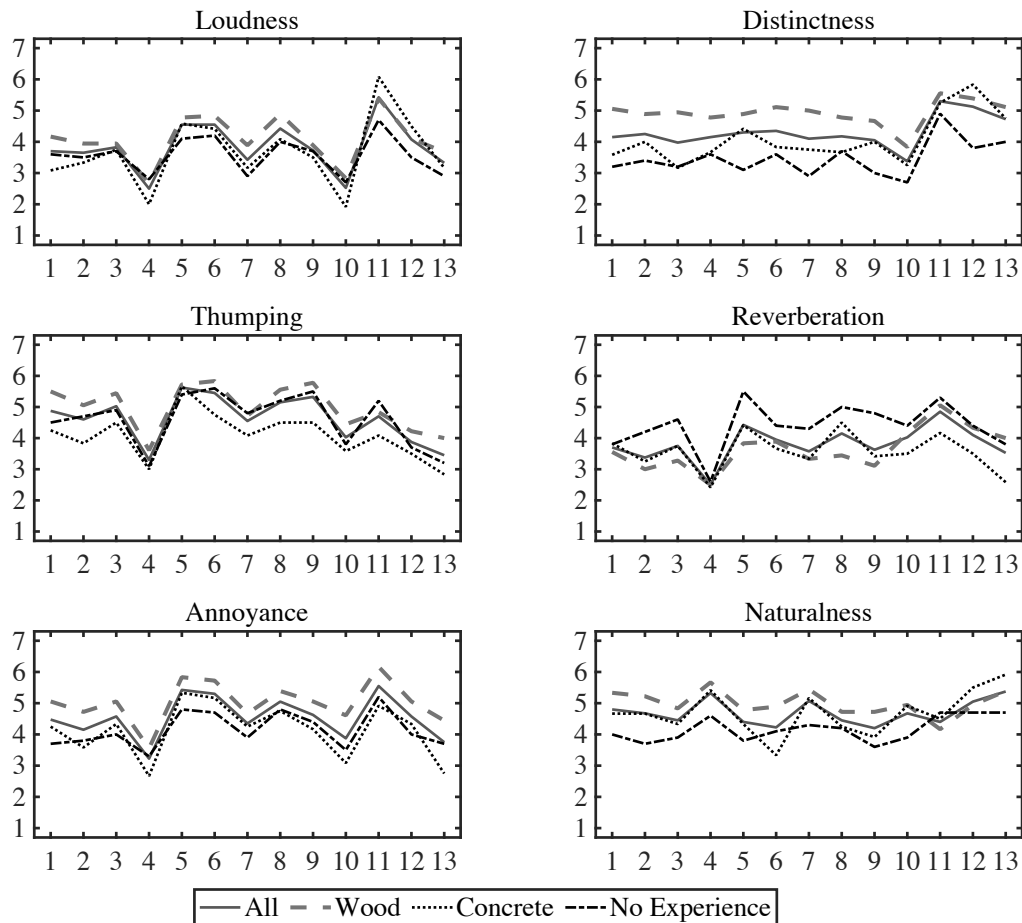


Figure 5.3 Average ratings by different groups of participants based on their familiarity with walking sound.

The curves show a clear distinction in all categories between the results from the subjects in group 1 and group 3. In general, the subjects in group 1 (i.e. subjects with experience with wooden floors) have perceived the sounds as louder, more distinct, annoying and natural and less reverberant than the subjects in group 3 (i.e. subjects with no experience with wooden floors).

The average ratings of group 2 in attributes such as distinctness, reverberation and naturalness fall often between the ratings of group 1 and 3. For example the subjects in group 2 have judged the majority of the sounds to be more distinct and natural than subjects in group 3, and less than the subjects in group 1. The order of rating for reverberation is the opposite. In other categories however, the curves for group 2 do not follow a clear trend relative to the curves of the other groups.

In loudness and annoyance categories, which are two determining factors for the perceived quality of a floor, the curves for the three groups are almost parallel, although their values are different. This means that although the perceived intensity of these attributes is different among different groups, the groups are similar in their judgement of different sounds relative to one another. This implies that even though the subjects in the three groups differ in their experience of the walking sound, and thus have different expectations regarding how footsteps should sound, there is a consensus among them about the relative loudness and perceived annoyance by the sounds.

Another noteworthy observation from group 1 is that the subjects in this group have, on average, perceived all the sound samples as louder and more annoying than the group including all participants. This can be explained by the fact that 7 out of 9 subjects in group 1, also reported that they had been regularly disturbed by walking sound from neighbors, and therefore could relate to the sounds as an annoying real-life situation.

The model floor M4, which is the prestressed floor, has received similar ratings from different groups in categories: loudness, thumping, reverberation and annoyance. The floor also has minimum average rating among the floor samples in these categories. Since all these categories relate to the feeling of discomfort, it can be concluded that the floor model M4 has the most acceptable acoustic performance among the presented floor examples.

A multiple comparison on the group means was done for different attributes, see Figure 5.4,. For these comparisons, analysis of variance (ANOVA) and t-test analysis methods were used. The ANOVA results showed that the mean ratings of distinctness are significantly different ( $F = 18.8$ ,  $p = 3 \times 10^{-6}$ ) between all groups. There are also significant differences between groups 1 and 3 in ratings of annoyance ( $p = 0.01$ ) and naturalness ( $p = 0.0007$ ), where the experienced subjects have found the sounds to be more annoying and more natural. Subjects in group 1 have also judged the sounds to be more annoying ( $p = 0.008$ ) than the subjects in group 2, who are familiar with walking sounds from concrete floors. The only significant differences between groups 2 and 3 is in their ratings of reverberation where the unexperienced listeners found the sounds more reverberant ( $p = 0.01$ ). No significant difference was found between the groups in their assessment of loudness.

It should be noted that the comparisons presented in this section are based on data from groups with a small number of subjects. Some differences between these groups are marginal, which means that the results might change if more subjects with slightly different judgements are added to each of the groups. For the same reason, the commonly used significance criterion of 0.05 for rejecting the null hypothesis, and declaring significant differences between data sets, was not used here. The reason is that this criterion might have resulted in misjudgment of the data, with such a small number of samples. Instead, the general trends were observed to explain the differences between the groups, and only  $p$ -values equal to or smaller than 0.01 were used as determinant of significant differences. To draw more solid conclusions about the influence of familiarity with the sounds, larger number of subjects might be required.

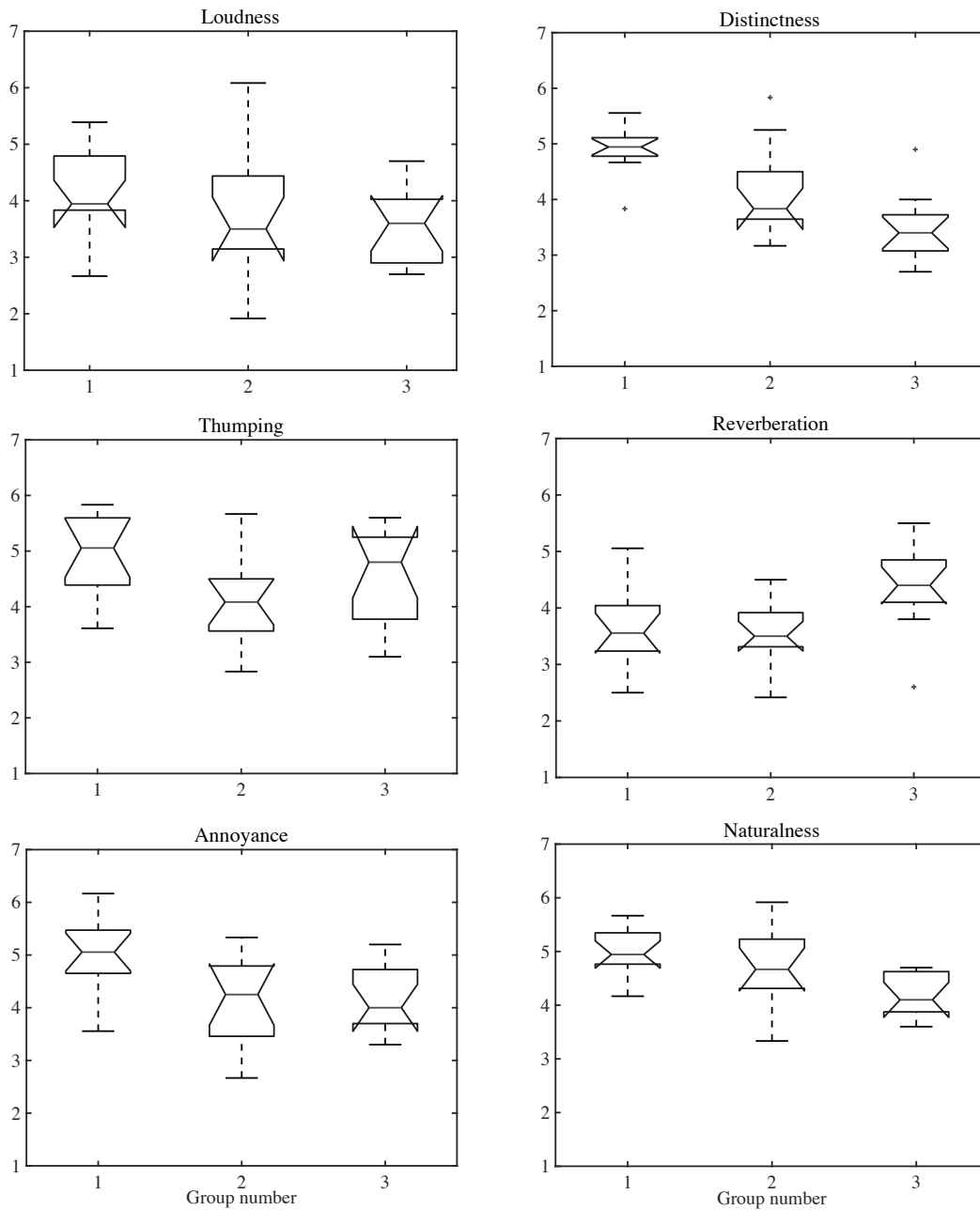


Figure 5.4 The distribution of ratings in each category for each group obtained by averaging the ratings of all sounds within the groups. Notched boxplot marking 95 % confidence intervals for the medians.

The observations from the comparisons between persons with different experiences lift the question whether for more credibility of the judgements, one should use only the data from experienced subjects, or on the contrary, treat the difference in judgement as a bias, and instead use all the data to reduce the effect of the bias. I believe that there is no singular right answer to this question, and choosing the right data depends on the purpose of the study. For example, if one wants to modify the floor design to remove a problem in an existing design, using experienced test subjects who are familiar with the sound and know what to listen for might be more useful. On the other hand, for a more general study such as here, where validation of the design tool is of interest, using the unbiased data from all types of subject might be more beneficial. Moreover, with the limited number of test subjects in our listening test, it is preferable to include all the data to obtain a better statistical stability.

### 5.3.2 Naturalness

The plausibility of the auralized walking sounds is investigated in this section. The naturalness ratings for all the participants as well as for group 1 are presented in Figure 5.5. The results for all participants (top plot) show that the perceived naturalness of all sound samples is mostly above 3.5, which is the mean value of the rating range. 75 % of the ratings to naturalness are 4 or more, 57 % are between 5 and 7 and 15 % are 7. This means that the majority of the participants found the auralized sounds plausible.

The walking sounds with the lowest perceived loudness (M4, M7, M10 and M13) are perceived as the most natural or plausible sounds. This can be due to the fact that the floors that are used in real buildings are often designed with better impact sound insulation performance than the floor objects presented here. Therefore, those floors that have softer sound might be more comparable with the real floors and thus, perceived as more natural.

When looking only at the results from the test subjects who lived in apartments with wooden floors, the naturalness of the sounds received even higher ratings. The boxplots in Figure 5.5 (bottom plot) present the data for group 1. The naturalness of the sounds is on average rated even higher than when all subjects are included. The increased naturalness rating is more noticeable for all the model floors, and the average rating for these floors ranges from 4.7 to 5.7, while the maximum average rating for the real floor examples is 5.4 (M13). Moreover, 7 of the model floors have an upper quartile value of 7 for naturalness, which means that the simulated walking sounds have been perceived as completely natural by 25 % of the experienced test subjects. Among the real floor examples, only the sample with -9 dB sound reduction is perceived as equally natural. Therefore, it can be concluded that the auralized walking sounds are perceived as plausible even among the experienced test subjects.

The low naturalness rating for the real floor (M11) with actual measured velocity amplitudes can be correlated with its high loudness ( $mean = 5.4$ ) and reverberation ( $mean = 4.8$ ) ratings, which also result in high perceived annoyance ( $mean = 5.5$ ) by the sound. So, when the sound is reduced by 6 and 9 dB, the perceived annoyance and reverberation were reduced, and the perceived naturalness increased accordingly. For the floor samples M12 and M13, respectively, 63 % and 80 % of the naturalness ratings are 5 or more.

In addition to the statistical data collected by the listening test, the subjects were asked whether they have any comment about the experiment. A comment, which was given by at least 7 participants about the naturalness of the sounds, was that some of the sound samples resulted in a rattling sound, probably generated by vibrations of a floor lamp, that made the total experience more plausible. One of the subjects associated the sound with rattling of dishes in the kitchen cupboards, which by that subject was perceived close to reality. Investigating this effect was not possible in the time frame of the thesis. Moreover, the test subjects who lived in concrete buildings or buildings where neighbors had a habit of walking with shoes, expected the walking sounds to contain higher frequencies, or as one subject pointed out, a ‘clacking’ sound.

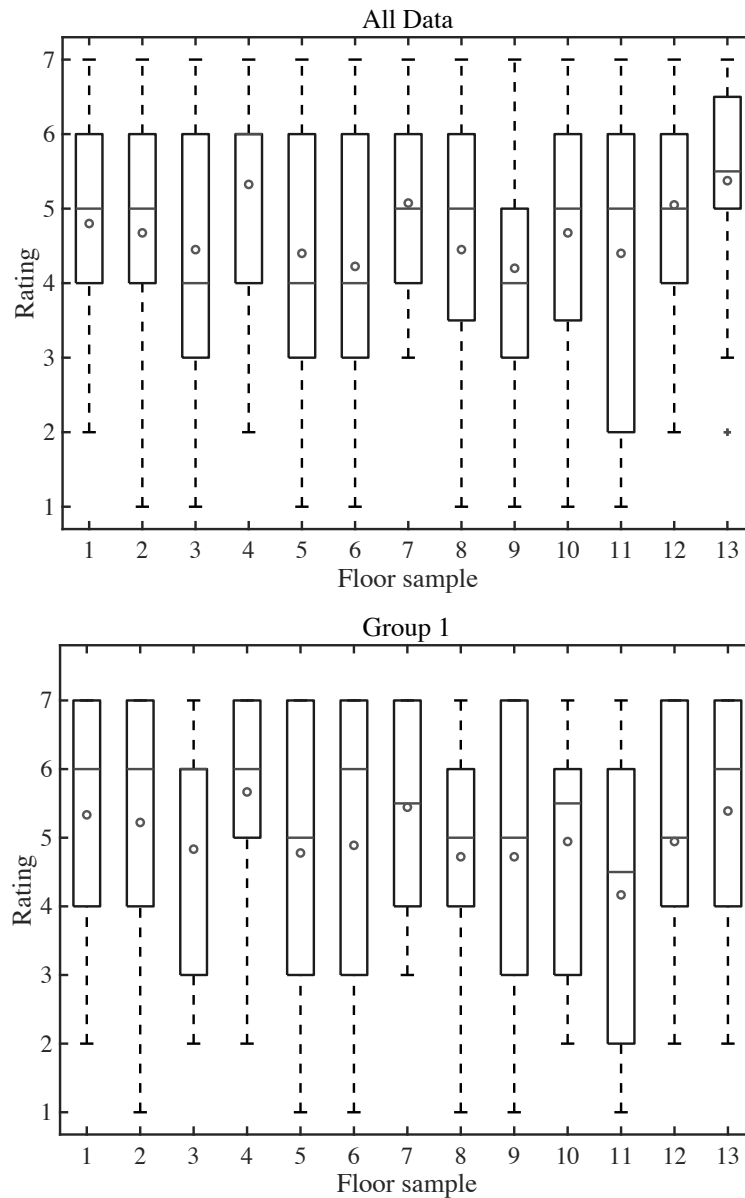


Figure 5.5 Assessment of naturalness of walking sound samples. The circles show the mean values of the data.

### 5.3.3 Correlations between the attributes

In this section linear regression models are used to investigate whether there are relationships between different subjective attributes of the walking sounds. For this purpose the average ratings of the 13 sound samples in each category were compared.

The correlation between the perceived annoyance and the other 5 attributes was first looked at. As it was expected, the results showed a strong correlation between perceived loudness and annoyance, with a coefficient of determination ( $R^2$ ) of 88 %. Reverberation also showed a high correlation with the annoyance ( $R^2 = 70\%$ ). It was also descriptively reported by the participants that they found the reverberant sounds very annoying. A relationship between the thumping and annoyance could be noticed in the results ( $R^2 = 65\%$ ), however, with weaker correlation than the loudness and reverberation. The regression curves and the confidence bounds for these attributes are presented in Figure 5.6.



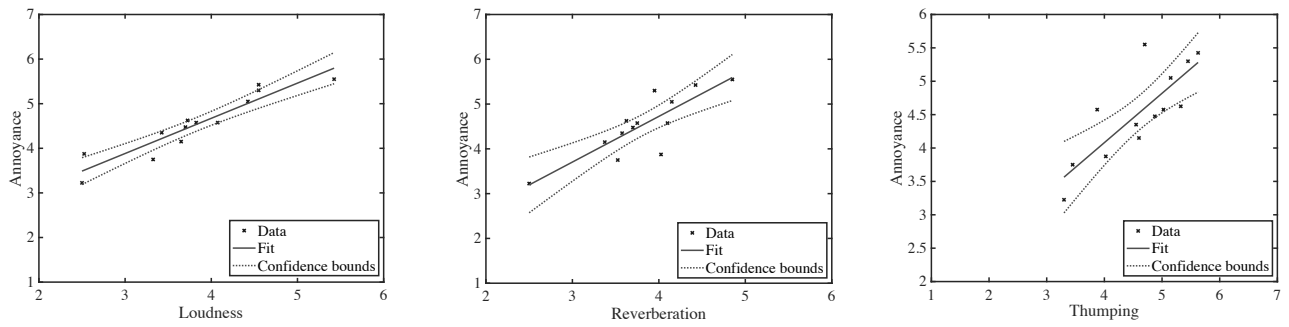


Figure 5.6 Correlation between annoyance and other subjective attributes of walking sounds.

The results also show a medium strong correlation between naturalness and annoyance ( $R^2 = 58\%$ ), which might have been assumed to be uncorrelated. Further investigations showed that the correlation becomes stronger for subjects in group 1 ( $R^2 = 72\%$ ). This implies that for the experienced subjects, the more plausible (natural) are the sounds, the more annoying they are perceived. This might be due to their experience of disturbance by such sounds. Very low correlation ( $R^2 = 14\%$ ) between the distinctness of footsteps and annoyance could be found.

The relationship between perceived loudness and thumping as well as reverberation were investigated. While loudness and thumping show a rather weak correlation ( $R^2 = 40\%$ ), the results for reverberation show a more clear relationship with loudness ( $R^2 = 61\%$ ), as shown in Figure 5.7.

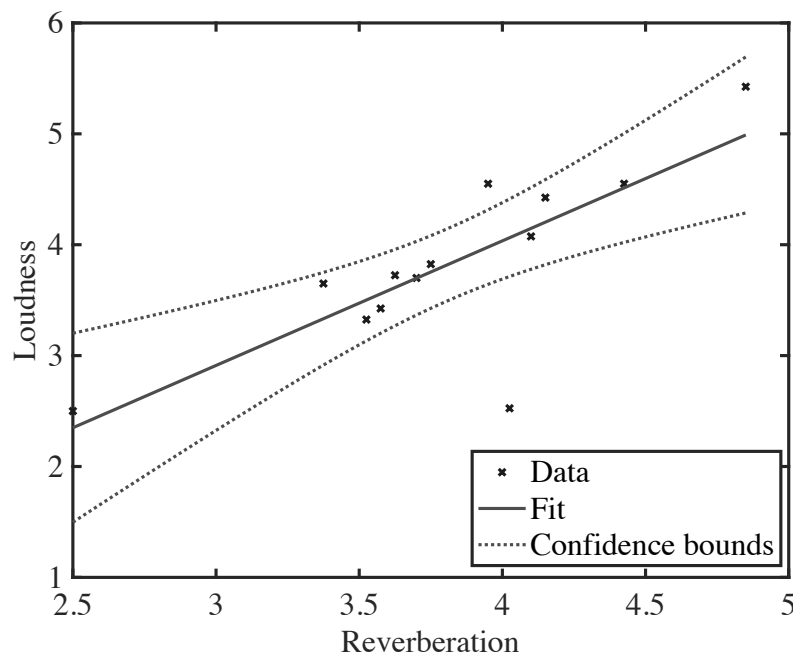


Figure 5.7 Linear regression analysis of perceived loudness and reverberation (decay time) of the sounds.

In a regression analysis, the relationship between perceived naturalness of the sounds and thumping as well as reverberation attributes was studied. The results (Figure 5.8) show a strong negative correlation between naturalness and thumping of the sounds ( $R^2 = 78\%$ ), which means that the walking sounds with very dominant and strong low frequency content were perceived as less natural. The analysis did not show any correlation between the perceived naturalness and reverberation of the walking sounds.

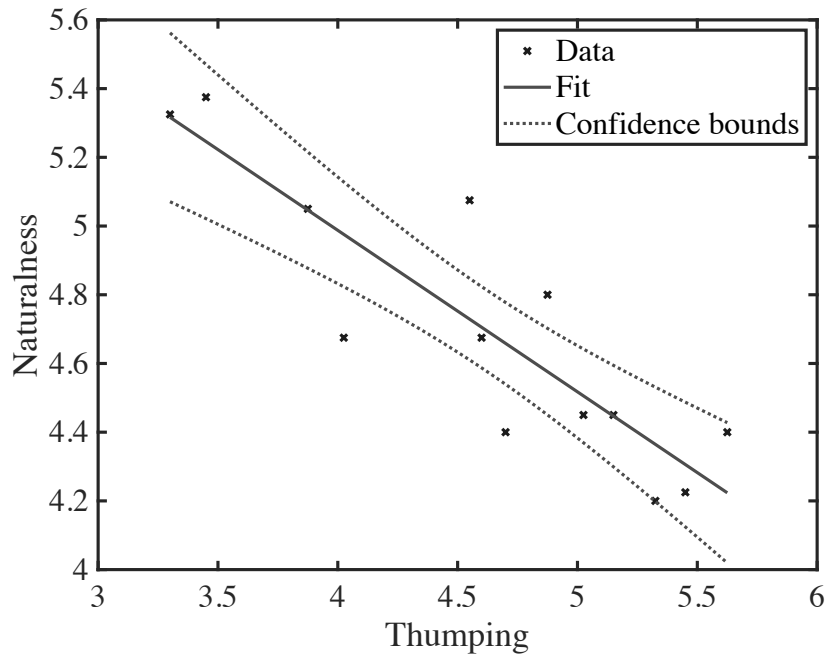


Figure 5.8 Linear regression analysis of perceived naturalness and thumping of the sounds.

#### 5.3.4 Discussion on floor designs

Among the floor samples used for the auralization, the walking sound for the prestressed floor model (M4) is perceived to have the least loudness, thumping, reverberation, and in general, is less annoying compared to the other floors. This could be explained by the fact that prestressing has shifted the first resonance of the prestressed floor up to 55 Hz, while the rest of the floors have their first resonances around 20 Hz, where the footsteps also have more energy. However, this improvement in the performance of the floor is not apparent from its impact sound insulation SNQ rating. In fact, the prestressed floor has an  $L_{nT,w,50}$  value close to at least 5 other model floors ( $61 \pm 1$  dB), which have perceived impact sound insulation performances different from M4. This can be explained by the fact that although prestressing the floor has significantly improved the performance of the floor at low frequencies, it has not provided much vibration isolation at high frequencies. At frequencies above 120 Hz the mobilities of floor model M4 becomes in the same order as the other lightweight floor models, see Figure 5.9.

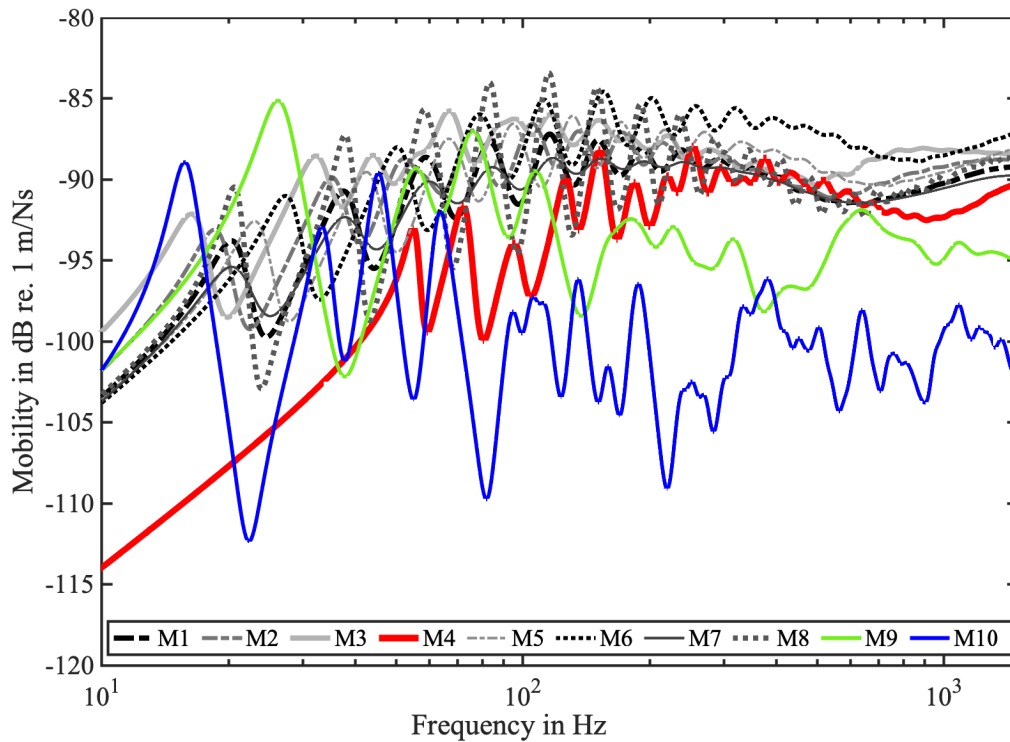


Figure 5.9 Mobilities of the floor models M1 to M10.

This underlines the insufficiency of the impact sound insulation SNQ rating in predicting the performance of lightweight floors under low-frequency excitations such as walking, and it once again emphasizes the importance of including frequencies as low as 20 Hz in the rating procedure of walking sound.

The floor with the second least perceived annoyance and loudness is the concrete floor model (M10). This floor is stiffer and much heavier than the lightweight model floors, which results in a shifting of the first resonance of the concrete floor down to 15 Hz and a reduction of its mobility amplitudes compared with those of the lightweight floor models, especially above 70 Hz. There is a good agreement between the low ratings of the perceived loudness and annoyance for this floor and its impact sound insulation rating, which is the lowest one among the investigated floor objects.

The floor models with low density (M5 and M6) and the model with low damping (M8) as well as the real lightweight floor (M11) are perceived to have the most annoying walking sounds with the majority of the ratings being 5 or more (70 % for M5, 68 % for M6, 60 % for M8 and 75 % for M11). Also, these sounds have on average higher ratings for perceived loudness with a mean value above 4.4. The subjective evaluation results for these floors are in agreement with the impact sound insulation values, as these floors also have the highest impact sound pressure levels.

Figure 5.10 illustrates the linear regression models to show the relationship between the impact sound insulation rating,  $L'_{nT,w}$ , and perceived annoyance as well as the perceived loudness.

Although the results show 77 % correlation between the perceived loudness and  $L'_{nT,w}$  values for the floor objects, the correlation between the annoyance and  $L'_{nT,w}$  values is only 53 %, which means that rating of impact sound insulation using  $L'_{nT,w}$  fails to predict the perceived annoyance in about half of the lightweight floors investigated here.

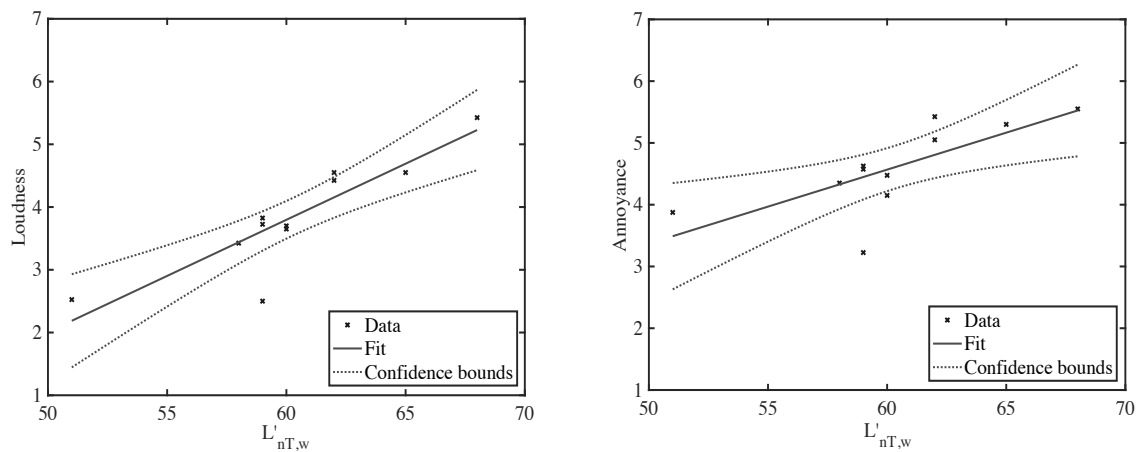


Figure 5.10 Relationship between impact sound insulation rating of the floors and the subjective loudness and annoyance of walking sounds.

By including the adaptation terms in the impact sound insulation evaluation, as shown in Table 5.5, the SNQ rating values for different floors become more similar to one another, and it gets more difficult to judge the differences in impact sound insulation performance of the floors.

Table 5.5 Weighted standardized impact sound pressure levels including the adaptation terms.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
$L'_{nT,w} + C_{I,50-2500}$	71	73	72	72	74	77	70	73	70	67	72
$L'_{nT,w} + C_{I,20-2500}$	85	86	83	73	85	87	83	89	81	77	81

The correlation between the perceptual attributes and the SNQ rating also decreases after including the adaptation terms, see Table 5.6. The  $p$ -values in Table 5.6 show the probability that the results are uncorrelated. The low correlations and the high  $p$ -values for the SNQ ratings including the adaptation terms could imply that the adaptation terms do not fit with the performance of the presented floors at low frequencies, and thus cannot sufficiently predict the perceived impact sound insulation of these floors. However, the adding of the adaption terms clearly identifies the two floors with lowest annoyance. The lack of correlation however needs further investigation.

Table 5.6 Coefficients of determination  $R^2$  and statistical significance probability values ( $p$ -values).

	Loudness		Annoyance	
	$R^2(\%)$	$p$ -value	$R^2(\%)$	$p$ -value
$L'_{nT,w}$	77	0.0003	53	0.009
$L'_{nT,w} + C_{I,50-2500}$	35	0.06	27	0.1
$L'_{nT,w} + C_{I,20-2500}$	39	0.04	45	0.02

## 6 Conclusions and future work

### 6.1 Conclusions

A virtual design studio for low-frequency impact sound is developed in this thesis. It is a tool that facilitates creating and listening to the acoustic field generated by impact forces on floors. In order to develop this tool, four main objectives are achieved, summarized as follows.

#### Force identification

A method based on the Least Mean Square algorithm (LMS) for the indirect measurement of forces when a person walks on a floor has been developed. For the very first time, the inverse time-domain force identification method based on the LMS algorithm has been applied to measure low frequency forces induced by a walker. With this method, multiple forces acting simultaneously on a system at known excitation positions can be measured. By using strain gauges, it was made possible to measure walking forces that are a combination of static load from the walker's body mass and dynamic forces created by the walking mechanism. Using the LMS-based force identification method to measure stance forces has several advantages in comparison with the conventional stance-force measurement techniques, such as instrumented treadmills and shoes equipped with force transducers. Unlike these techniques, the LMS-based method gives freedom to the walker to choose the path and speed of walking without modifying the footwear, altering the natural walking style or requiring practice. The stance forces acquired in this study are qualitatively in accordance with the force signals given in the literature. The influence of floor material, type of footwear and walker's weight on the force signals and spectra have been investigated. The deviation between impact forces made by a standard tapping machine and stance forces during walking has been examined.

Measured walking force signals for different walkers illustrated that although there is a general characteristic shape for the human footstep-force signal, the amplitudes of different phases and frequency contents of the walking forces vary between persons. Regardless of type of footwear, the walking forces are largely influenced by the style of walking. Different persons walk differently, and walking forces depend on many individual parameters besides body weight. Due to this individuality in walking, walking forces can vary widely.

From the measurements it was concluded that a walker is mainly a force source. However, later during the auralization it was discovered that the very first resonances of the lightweight floor appear in the measured walking forces, and when the walking sound was auralized, the floor resonances, where the floor mobility is high, became oscillations that were audible as a ringing sound. Therefore, a piece-wise curve smoothing procedure was applied in the time domain to remove these oscillations from the force signals without filtering the important high frequencies of the force corresponding to the heel strike.

By looking at the impact forces made by the tapping machine on two different floors (a wooden floor and a heavier and stiffer version of the wooden floor, made by adding cement boards on top), it can be noticed that the amplitude and frequency content of the impact forces change by changing the surface properties. This illustrates that the tapping machine might not behave as a pure force source on many lightweight structures. The third octave band tapping machine force levels on the two test floors show a large difference at 20 Hz, where a dip occurs in the force spectrum for the lighter floor. The dip is

shifted to lower frequencies for the heavier floor structure. This shift can be explained partly by a decrease of the resonance frequencies of the heavier cement-wood floor and partly by variations in the frequency of the impacts of tapping machine. In the frequency range 20–50 Hz, the impact force amplitude made by the tapping machine becomes comparable with stance forces made by different walkers. It shows that the tapping machine can provide enough input power to excite the floor in this frequency range, and therefore can be used for standard evaluation of impact noise even down to 20 Hz. However, it is important to consider that in the frequency range between 20 and 50 Hz, the large force amplitudes made by the tapping machine mainly correspond to the 10 Hz line spectrum caused by the fundamental frequency of the hammer impacts. Therefore, if the floor has pronounced resonances in this range, at frequencies other than harmonics of 10 Hz, it is likely that the tapping machine cannot excite them, and they remain unnoticed in the impact noise evaluation of the floor. Excitation of these floor resonances by walking can cause high impact noise levels at low frequencies and be the source of discrepancy between the standard impact noise evaluation results and the perceived performance of the floor.

### **Model for lightweight floor**

In the thesis a simple analytical model of a floor structure was used to calculate the vibrational response due to external forces in order to obtain variation of the vibration of the floors in time and space. Although the developed model is limited to cases of homogeneous simply-supported plates, it provides the possibility to investigate the effects of different parameters such as floor density, stiffness and damping on the impact sound insulation and the generated impact sound. However, the design tool is not limited to this type of floor, and if needed, a more complex floor model, e.g. from using a Finite Element Method could be used to calculate the vibrational responses of a specific floor to an impact force.

### **Auralization**

An impact sound auralization tool is established here, using ceiling-mounted loudspeaker arrays. For this, transfer functions between prescribed volume velocity created by the vibrations of the floor and electrical signal applied to the loudspeakers is established. The comparison between the auralized walking sound levels in the listening lab with the sound levels measured in-situ showed fair agreement.

In the auralization, the coupling between the room and the floor modes, which in real buildings can result in amplification of sound at certain frequencies, cannot be reproduced for all room sizes. We are constrained to the dimensions of the listening lab, and only the floor-room coupling of the rooms with similar dimensions to that of the lab can be simulated. However, this listening environment provides both correct visual and auditory stimuli, representative of a room with similar characteristics in a real building, meaning that the results are not biased by e.g. discrepancy between visual and auditory impression.

An advantage of the presented auralization tool over other auralization methods, using e.g. headphones or ambisonic loudspeaker arrays, is that it is not limited to a certain listening position and does not require determining a sweet spot. The listener can be placed anywhere in the room and e.g. localize and follow the walker, as is the case in reality.

## **Demonstration of the design studio for low frequency sound**

For the auralization, a different approach is used than usual. Instead of creating a virtual sound field, like e.g. with ambisonics, the vibration of the floor is simulated by an array of loudspeakers. In order to convert floor vibrations to the impact sound in the room, we just need to compensate for the internal transfer function of the loudspeakers, which is measurable. The factors such as receiver's distance from the loudspeaker, directivity of the loudspeaker and sound absorption properties of the room do not need to be considered in this auralization method.

Results of the listening test, which was made using the auralized walking sound for different floor models, showed that 75 % of the participants found the plausibility of the auralized walking sounds above the average of the rating range. Familiarity of the test subjects with the impact sound generated by walking is a determining factor which can affect the subject's expectation and consequently judgement of the sound. For example, those who lived in concrete buildings expected the walking sounds to contain higher frequencies. The listening test results for persons who had experience with walking sound from wooden floors and persons who were unfamiliar with it showed significant differences in the perception of annoyance, naturalness and distinctness of the walking sounds. Persons with prior familiarity judged the walking sounds as more annoying, more natural and more distinct. The results, however, are difficult to validate with respect to experiencing the walking sound at home, since real-time comparison of the two cases is not possible. A potential future investigation could be to select a group of persons living in buildings with a certain floor design and perform the listening tests both at their home and in the lab, using the same floor design for the auralization of the walking sound. Such a comparison might be the closest one could get to validating the auralization process. Furthermore, due to the limited number of participants, a further statistical analysis on the effect of familiarity of subjects with the sound could not be performed, but for future studies this factor should be taken into account for this type of listening tests.

The results from the listening tests showed that there is a high correlation between perceived loudness of the walking sounds and annoyance. A high correlation was also found between reverberation and annoyance. The highest reverberations were perceived for the floor models with lower damping or lower density than the other floors. The results are as expected and are consistent with respect to the variations in the floor parameters. This shows that the design tool can reproduce the physical variations of the floor design in the auralized sounds.

The prestressed floor model M4 was perceived to have the quietest and least annoying walking sound among all the samples. It was also judged to have the least reverberant and thumping sound, which are also parameters connected to perception of annoyance. This design modification can be a potential improvement for lightweight floors, which could be studied further. However, it should be pointed out that prestressing can move the floor resonances to higher frequencies and weaken the impact sound insulation of the floor at those frequencies. On the other hand, the higher frequencies are easier to insulate using vibration dampers and sound absorbers.

Although the prestressed floor was subjectively judged to have the best performance among all the tested floor objects, the measured standardized impact sound insulation of the floor did not show any advantage over most of the other floors. The reason could be that prestressing the floor had shifted the first resonance from circa 20 Hz to 55 Hz and decreased the floor mobility of the prestressed floor

below the first resonance, compared with the other lightweight floor objects. But, since the floor model M4 is still lightweight, and at frequencies above 120 Hz has a mobility in the same order of amplitude as the other model floors, prestressing does not affect the standardized impact sound insulation, which is evaluated mainly based on frequencies above 120 Hz.

## 6.2 Future work

The presented virtual design studio for low-frequency impact sound facilitates further research and investigation in the following areas.

Here, only the vertical component of walking forces is taken into account. Investigating the influence of tangential components of the walking forces on the localization and perception of naturalness of the walking sound can be a potential future step.

Binaural recording of sound samples in situ and in laboratory, and comparing the sounds in a listening test, can be a future step. This comparison can also be a way to further investigate the quality of the auralization tool. The effect of rattling sounds on the perception of the walking sounds can be investigated more thoroughly in the future. It might lead to a conclusion that adding an artificial rattling sound, which is adapted to the visual properties of the room, can improve the plausibility of the sounds and generate a more realistic perception.

Performing the listening tests in a listening room furnished as a living room, and without using headphones, enables us to create a more realistic impact sound experience than the conventional listening tests in laboratory environments, using headphones to reproduce the sound. In our experimental setup the test subjects have more freedom to move which makes it easier for them to immerse in the acoustic environment. This, at the same time makes the experiments harder to control. For example, the subjects might adapt their sitting position or direct their attention to other sensory stimulus in the room in order to compensate for the discomfort caused by exposure to the low-frequency sound. In the future, such activities can be tracked and included in the investigation results.

Although the tool is developed to be used in the listening laboratory at Chalmers, it can be modified and adapted to other auralization rooms with dimensions different from our lab. However, one should bear in mind that the geometry and acoustic properties of the room influences the impact sound pressure levels, e.g. at low frequencies the coupling between the room modes and the floor modes can result in higher sound pressure levels compared with when there is no such coupling.

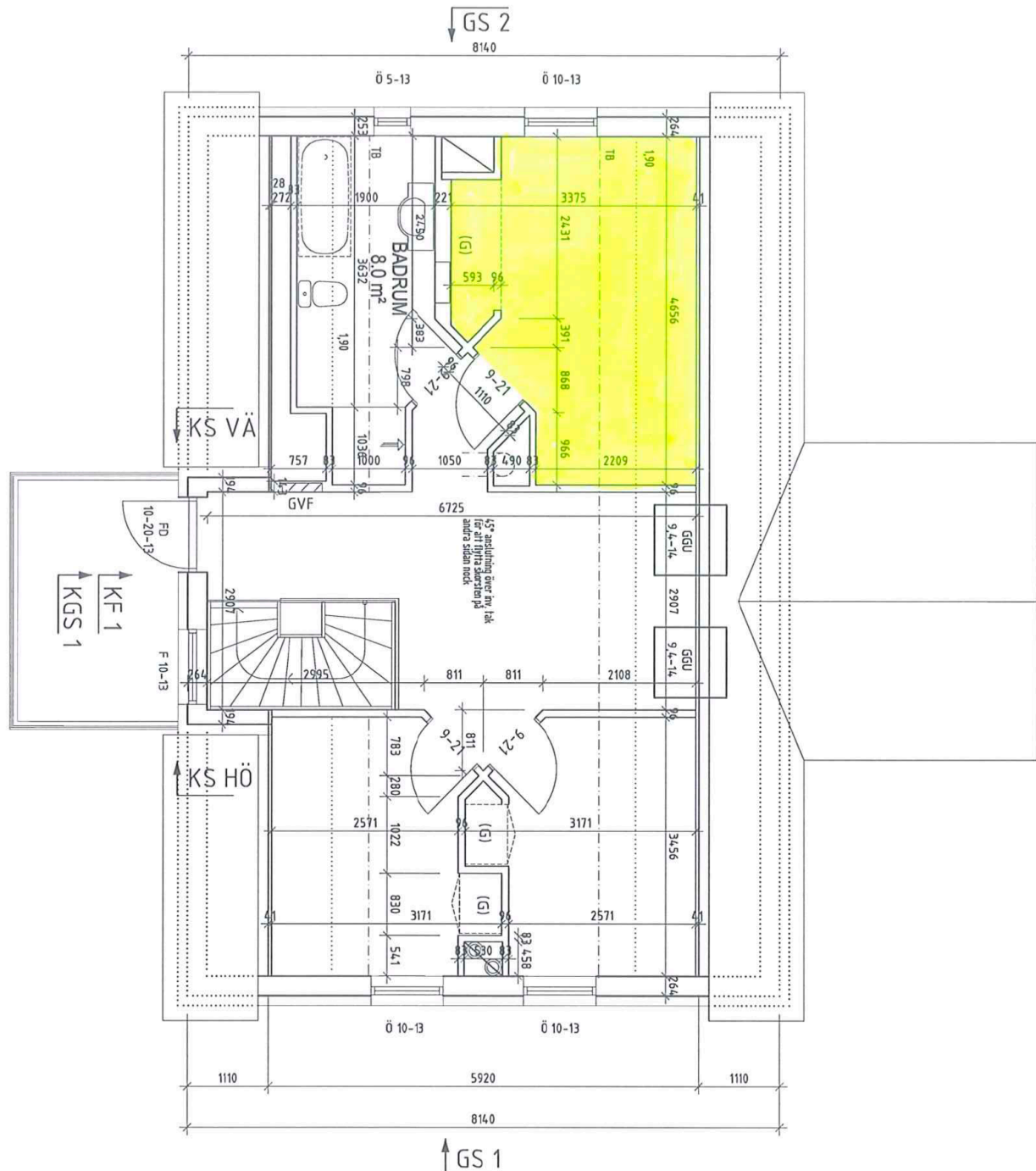
Finally, the virtual design studio can be used as a valuable tool for design of new floors and redesign of existing floors. The tool can be used in the future for investigating the influence of different floor properties and walking characteristics on the perception of impact sound in buildings even without having access to a real building.



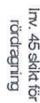
## Appendix A

Plan drawings of the two-storey house where the floor vibration measurements were performed are presented in the following. The highlighted rooms denote the sending and the receiving rooms. The room called ‘Vardagsrum’ was the receiving room in our measurements.

## Sending room



## Receiving room



# Appendix B

## Test instructions

In this listening test you are asked to imagine you are sitting in a living room. Sit comfortably on the sofa at the position that the instructor shows you. Make sure that you sit at the same position on the sofa throughout the entire experiment.

During this test you will be asked to evaluate a number of walking sounds using different descriptors. For the best outcome you are asked to judge the sounds using the descriptors independent from one another.

The descriptors are: **LOUD, DISTINCT, THUMPING, REVERBERANT, ANNOYING** and **NATURAL**. A short description of the intended meaning of the terms is given below:

**Loudness:** corresponds to the perceived sound pressure

**Distinctness:** corresponds to distinguishability and clarity of the successive footstep sounds

**Thumping:** corresponds to the presence of prominent and high energy low-frequencies in the sound

**Reverberant:** corresponds to the decay time of the sound

**Annoying:** corresponds to the perceived annoyance by the sound

**Natural:** corresponds to naturalness (plausibility) of the presented walking sound

### Note:

- You are free to withdraw the experiment or leave the room at any time and for any reason.
- You will be anonymous, and your personal information will be treated confidentially.

Before starting the test, please answer the following questions:

Participant's code:

Age

Gender

Have you ever heard neighbours walking upstairs? If yes, how often?

Have you ever been disturbed by walking sound from the neighbours? If yes, how often?

If the answer to any of the questions above is yes, do you know the type of the floor (concrete or wood)?

You can now start the listening test by using the mouse and the screen in front of you. **Listen to each sample for at least 20 seconds.** The first three examples are for training.

**Remember to press the**

Next

**button after completing evaluation of each sound.**

Would you like to add any comment about the presented sound samples or this listening test in general?

Stop

How LOUD is the sound? (1:Low; 7:High)	<div><div></div></div>	4
How DISTINCT is the sound? (1:Not distinct; 7:Very distinct)	<div><div></div></div>	6
How THUMPING is the sound? (1:Not thumping; 7:Very thumping)	<div><div></div></div>	4
How REVERBERANT is the sound? (1:Not reverberant; 7:Very reverberant)	<div><div></div></div>	1
How ANNOYING is the sound? (1:Not annoying; 7:Very annoying)	<div><div></div></div>	3
How NATURAL is the sound? (1:Artificial; 7:Natural)	<div><div></div></div>	7

1/26

Next



## Bibliography

- [1] B. Falk, "Wood as a Sustainable Building Material," *Forest Products Journal*, vol. 59, no. 9, pp. 6-12, 2009.
- [2] "Market Statement 2018 – SWEDEN: UNECE Timber Committee Market Discussion," Agency, Swedish Forest, Vancouver, Canada, 2018.
- [3] "The Delegation for Sustainable Cities - a national arena for sustainable urban development," 2008. [Online]. Available: <http://www.hallbarastader.gov.se/Bazment/hallbarastader/sv/in-english.aspx>.
- [4] U. Save-Öfverholm, "SB11 - Swedish Sustainable Building - Research – Development – Innovation – Implementation," Forskningsrådet Formas, 2011.
- [5] K. Mahapatra and . L. Gustavsson, "General conditions for construction of multi-storey wooden buildings in Western Europe," School of Technology and Design, Växjö University, Växjö, 2009.
- [6] R. Jonsson, "Prospects for timber frame in multi-storey house building in England, France, Germany, Ireland, the Netherlands and Sweden," Växjö University, Växjö, Sweden, 2009.
- [7] "Wood construction in Sweden: Fact Sheet," Government Offices of Sweden-Ministry of Enterprise and Innovation, 2017.
- [8] J. Forssén, W. Kropp, J. Brunskog, S. Ljunggren, D. Bard, G. Sandberg, F. Ljunggren, A. Ågren, O. Hallström, H. Dybro, K. Larsson, K. Jarnerö, L.-G. Sjökvist, B. Östman, K. Hagberg, Å. Bolmsvik, A. Olsson, C.-G. Ekstrand and M. Johansson, "Acoustics in wooden buildings State of the art 2008," SP Technical Research Institute of Sweden, Borås, Sweden, 2008.
- [9] C. Simmons, K. Hagberg and E. Backman, "Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements," AkuLite Report 2, SP Report 2011:58, 2011.
- [10] F. Ljunggren and E. Backman, "Data från byggakustiska fältmätningar och enkätundersökningar i flerfamiljshus," AkuLite Rapport 8, LTU Rapport 2013, SP Rapport 2013:10, 2013.
- [11] F. Ljunggren, C. Simmons and K. Hagberg, "Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound," *Applied Acoustics*, vol. 85, pp. 57-68, 2014.
- [12] R. Öqvist, F. Ljunggren and R. Johnsson, "Walking sound annoyance vs. impact sound insulation from 20 Hz," vol. 135, no. 2018, pp. 1-7, 2018.
- [13] "ISO 16283-2:2015 : Acoustics -- Field measurement of sound insulation in buildings and of building elements -- Part 2: Impact sound insulation," 2015.
- [14] "ISO 717-2:2013 : Acoustics -- Rating of sound insulation in buildings and of building elements - - Part 2: Impact sound insulation," 2013.
- [15] "Svensk Standard SS 25267:2015: Acoustics – Sound classification of spaces in buildings –

Dwellings," 2015.

- [16] "God bebyggd miljö – förslag till nytt delmål för buller inomhus - Resultat från projektet BETSI," Boverket, Karlskrona, 2010.
- [17] L. Cremer, M. Heckl and B. Petersson, *Structure-Borne Sound: Structural Vibrations and Sound Radiation at Audio Frequencies*, Springer, 2005, p. 620.
- [18] M. Lievens and J. Brunskog, "Model of a person walking as a structure borne sound source," in *Proceedings of the 19th International Congress on Acoustics*, Madrid, Spain, 2007.
- [19] S. C. Wearing, S. R. Urry and J. E. Smeathers, "The effect of visual targeting on ground reaction force and temporospatial parameters of gait," vol. 15, no. 8, pp. 583-591, 2000.
- [20] V. Racic and J. Brownjohn, "Stochastic model of near-periodic vertical loads due to humans walking," *Advanced Engineering Informatics*, vol. 25, no. 2, pp. 259-275, 2011.
- [21] E. R. C. Draper, "A treadmill-based system for measuring symmetry of gait," *Medical Engineering & Physics*, vol. 22, no. 3, pp. 215-222.
- [22] L. Mattias, "Force measurements of a person walking on a lightweight floor power transfer," in *Proceedings of DAGA 2008*, Dresden, Germany, 2008.
- [23] W. Adachi, N. Tsujiuchi, T. Koizumi, M. Aikawa, K. Shiojima, Y. Tsuchiya and Y. Inoue, "Development of walking analysis system consisting of mobile force plate and motion sensor," in *Proceeding of Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Bostyn, Massachusetts, USA, 2011.
- [24] V. Racic, A. Pavic and J. M. W. Brownjohn, "Experimental identification and analytical modelling of human walking forces: Literature review," *Journal of Sound and Vibration*, vol. 326, pp. 1-49, 2009.
- [25] N. M. M. Maia, Y. E. Lage and M. M. Neves, Recent Advances on Force Identification in Structural Dynamics, InTech, 2012, p. 103–132.
- [26] N. Kawabata, H. Hayata, N. Hu and H. Fukunaga, "Modal Measurements Using Strain Sensors and Application to Impact Force Identification," in *International Symposium on Inverse Problems in Engineering Mechanics 2003 (ISIP 2003)*, Nagano, Japan, 2003.
- [27] T. J. Kreitinger, Force identification from structural response (Doctoral Dissertation), Albuquerque, New Mexico: The University of New Mexico, 1989.
- [28] D. C. Kammer and A. Steltzner, "Input Force Estimation Using an Inverse Structural Filter," *Journal of Vibration and Acoustics*, vol. 123, no. 4, pp. 524-532, 2001.
- [29] D. C. Warwick and J. J. Gilheany, "Estimation of dynamic forces via modal decomposition of operational deflection shape measurements," *The Journal of the Acoustical Society of America*, vol. 93, no. 4, 1993.
- [30] A. Berry, O. Robin and F. Pierron, "Identification of Dynamic Loading on a Bending Plate Using the Virtual Fields Method," *Journal of Sound and Vibration*, vol. 333, pp. 7151-7164, 2014.



- [31] P. A. Nelson and S. J. Elliot, *Active Noise Control*, 5th edition ed., A. Press, Ed., London, 2000.
- [32] W. Kropp and K. Larsson, "Force estimation in the time domain by applying an LMS algorithm," in *Proceedings of Conference on Noise and Vibration: Emerging Methods (Novem)*, Saint-Raphaël, France, 2005.
- [33] M. Sturm, A. Moorhouse, W. Kropp and T. Alber, "Robust calculation of simultaneous multichannel blocked force signatures from measurements made in-situ using an adaptive algorithm in time domain," in *Proceedings of 20th International Congress on Sound and Vibration (ICSV20)*, Bangkok, Thailand, 2013.
- [34] M. Sturm, A. Moorhouse, W. Kropp and T. Alber, "Robust force identification for complex technical structures with single degree of freedom excitation using an adaptive algorithm in time domain," in *Proceedings of AIA-DAGA 2013*, Merano, Italy, 2013.
- [35] E. O. Doebelin, *Measurement Systems Application And Design: 5th Edition*, New York: McGraw-Hill, 2003.
- [36] M. Serridge and T. R. Licht, *Piezoelectric Accelerometers and Vibration Preamplifier: Theory and Application Handbook*, Brüel & Kjær, 1986.
- [37] TML Strsin Gauges Catalog, Tokyo: Tokyo Sokki Kenkyujo Co., Ltd.
- [38] R. Pagán, M. Recuero and W. Kropp, "Wave Content of Wooden Floors," *Acta Acustica united with Acustica*, vol. 100, no. 1, pp. 67-78, 2014.
- [39] L.-G. Sjökvist, *Structural sound transmission and attenuation in lightweight structures*, Göteborg, Sweden: PhD dissertation, Chalmers University of Technology, 2008.
- [40] A. Homb, "Hybrid cross-laminated timber floors. Comparison of measurements and calculations," in *Proceedings of the 22nd International Congress on Acoustics (ICA2016)*, Buenos Aires, Argentina, 2016.
- [41] P. A. Nelson and S. J. Elliott, *Active control of sound*, London, UK: Academic Press, 1992.
- [42] "8020B Studio Monitor: 8020B Data Sheet," [Online]. Available: <https://www.genelec.com/support-technology/previous-models/8020b-studio-monitor>. [Accessed 24 March 2019].
- [43] L. L. Beranek, *Acoustics*, Cambridge, USA: Acoustical Society of America, 1996.
- [44] R. Stürzenbecher, K. De Borst and J. Eberhardsteiner, "Cross Laminated Timber: A multi-layer, shear compliant plate and its mechanical behavior," in *World Conference on Timber Engineering-WCTE 2010*, Riva del Garda, Italy, 2010.
- [45] Z. Guo, *Principles of Reinforced Concrete*, USA: Elsevier, 2014.
- [46] C. E. Osgood, G. J. Suci and P. H. Tannenbaum, *The measurement of meaning*, Oxford, England: University of Illinois Press, 1957.
- [47] E. Nilsson and P. Hammer, "Subjective evaluation of impact sound transmission through floor

structures," Lund University, Lund, Sweden, 1999.

[48] P. Thorsson, "Laboratory Listening Tests," AkuLite Report 7, Chalmers Report 2013:5, 2013.